Hadrons in Nuclei

Predictions and Observables

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Why study in-medium hadrons?

- Nucleon-meson physics in medium
  → Link to Nucleon-Resonance Properties
- Density may restore symmetries of QCD
  - Drop of condensates
  - Degeneracy of chiral partners
- Nucleus as a ‚microdetector':
  - access to production- and form.-times in quark-fragmentation, color transparency
- In-medium properties may signal exotic states of nuclear matter (e.g.: QGP)

→need baseline effects in normal nuclear matter

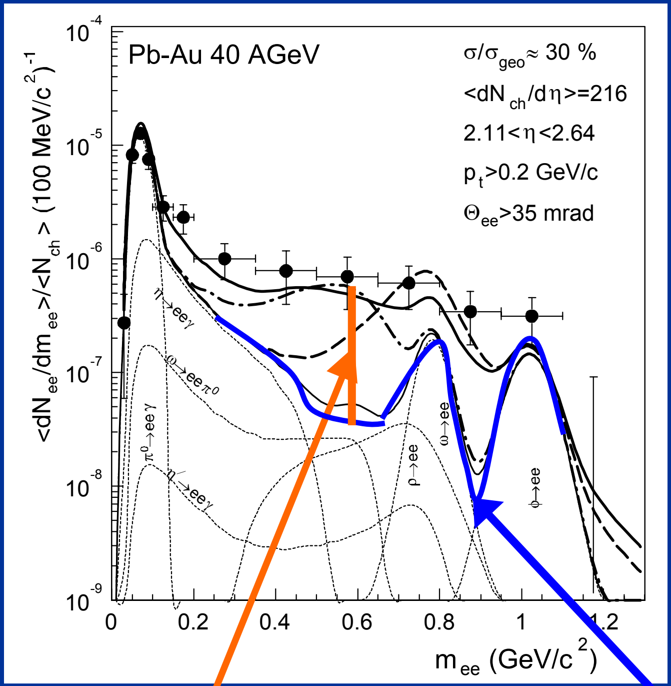
In-medium changes: experiment 2000

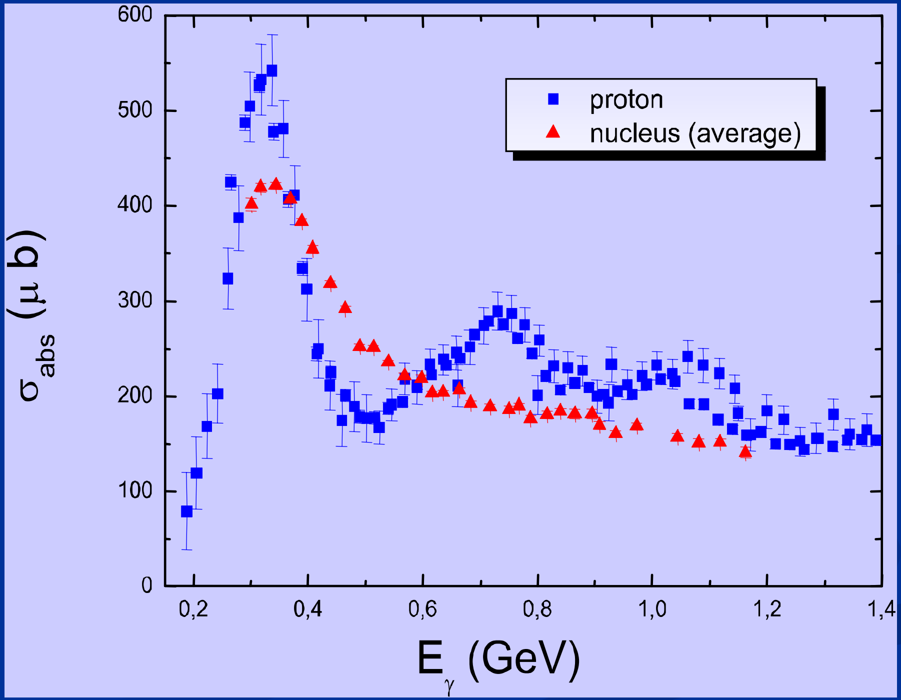
Evidence for QGP at Cern

Invariant (e+e-) mass spectrum

Total photoabsorption cross section

explained by spectral change of ρ meson in dense, (hot) matter





CERES effect

Cocktail plot of free sources

In-medium changes: experiment 2003

- evidence for QGP at RHIC:
  Jet Quenching
- Related Photonuclear Effect at HERMES:
  Jet Quenching

Equilibrium vs. Nonequilibrium

or: why it is better to work with microscopic probes on nuclei

- URHIC signal sums over very different stages of reaction:
  - Start: highly non-equilibrated, very high density
  - End: equilibrated, high temperature, low density
    - In *thermal* equilibrium all infos about interactions are lost
- Theories assume equilibrium for calculating hadronic in-medium properties
- Photonuclear reactions much closer to (cold) equilibrium, low but constant density throughout

Observables

- Experimental data:
  incoherent photo- and electroproduction of hadrons on nuclei from 100 MeV (MAMI, ELSA) over few GeV (JLAB) to ~20 GeV (HERMES)
- Experiment:
  - weak ISI ➔ γ best
  - FSI
    - Hadronic, e.g. $\phi \to K^+K^-$ difficult
    - Semihadronic, e.g. $\omega \to \pi^0 \gamma$ possible
    - Electromagnetic, e.g. $\omega \to e^-e^-$ best

Observables

- FSI important:
  - *attenuation* of primary particle
    can be treated by *Glauber* (standard)
  - *Side feeding* from other channels,
    e.g. γ N $\rightarrow$ π N, π N' $\rightarrow$ K Λ
    must be treated by *Coupled Channels* (BUU) Method

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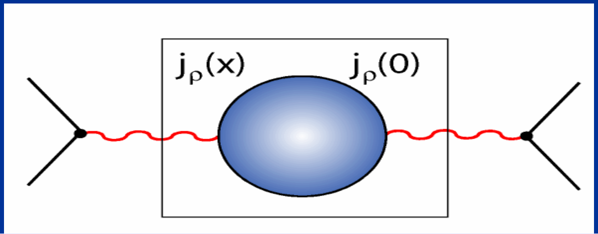
Vector Mesons: Hadronic Tensor

- determines electromagnetic coupling to hadrons:



$$\Pi^{\mu\nu} \sim \int d^4x\, e^{iqx} \langle 0 | T\left[j^\mu(x) j^\nu(0) \right] | 0 \rangle$$
$$= \left(q^2 g^{\mu\nu} - q^\mu q^\nu \right) \Pi\left(q^2 \right)$$

Vector Mesons: Hadronic Tensor

Total cross section for hadron production:

$$\sigma\left(e^+e^- \rightarrow hadrons\right) = -\frac{4\pi\alpha}{q^2}\Im\Pi\left(q^2\right)$$

Experimentally known for free hadrons

contains spectral information about hadrons

Vector Mesons: Hadronic Tensor

Vector Meson Dominance

Photon ≅ Vector meson ($J^\pi=1^-$)

$$\Pi^{\mu\nu}(q) \sim \int d^4x\, e^{iqx}\langle 0|T\left[j^\mu(x)j^\nu(0)\right]|0\rangle$$

$$= \int d^4x\, e^{iqx}\langle 0|T\left[\rho^\mu(x)\rho^\nu(0)\right]|0\rangle \frac{m_\rho^2}{g_\rho^2} = \frac{m_\rho^2}{g_\rho^2} D_\rho^{\mu\nu}(q)$$

ρ meson propagator

Spectral Function

$$\mathcal{A}(\omega,\vec{q}) = -\frac{1}{\pi}\Im D(\omega,\vec{q}) \sim \Im\Pi(\omega,\vec{q})$$

- Two ways:
  - Determine constraints on in-medium Π from QCD sum rules
  - Calculate in-medium Π in hadronic model

QCD Sum Rule

only ‚clean‘, but indirect connection between hadronic and quark world

Compare spectral function in time-like region with OPE of current-correlator for space-like distances

$$\frac{Q^2}{\pi}\int_0^\infty ds\,\frac{\Im\Pi(s)}{s\left(s+Q^2\right)} = -\frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)\ln\frac{Q^2}{\Lambda^2} + \frac{m_q\langle\bar{q}q\rangle}{Q^4} + \frac{1}{24}\frac{\langle\frac{\alpha_s}{\pi}G^2\rangle}{Q^4} + \frac{\langle(\bar{q}q)^2\rangle}{Q^6} + \ldots$$

- Lhs dominated by soft scale ~ m_ρ
- Rhs separates hard scale ~ Q^2 from soft scale (condensates)

- Model condensate (ρ)
- Parametrize $\Im\,\Pi$ in terms of few parameters, to be extracted from sum rule

$$\Im\Pi(s) = \pi F \frac{S(s)}{s}\Theta(s_0 - s) + \frac{1}{8\pi}\left(1 + \frac{\alpha_s}{\pi}\right)\Theta(s - s_0)$$

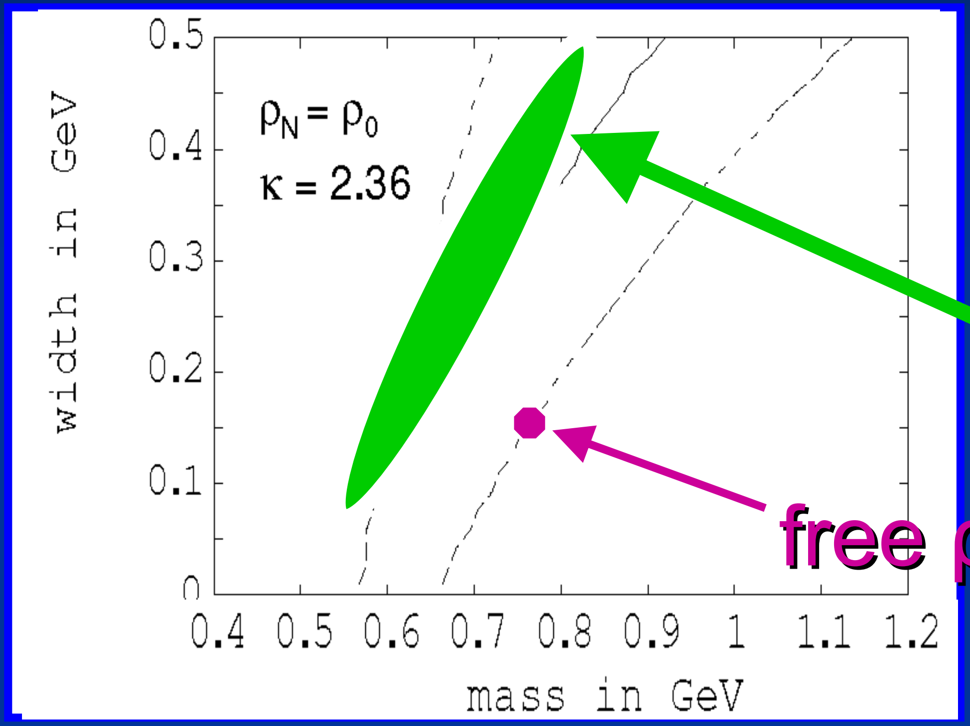
- Hatsuda-Lee (1991):

$$S(s) = \delta(s - m_\rho^2) \Longrightarrow m_\rho$$

- Leupold-Peters-Mosel (1998):

$$S(s) = \frac{1}{\pi}\frac{\sqrt{(s)}\Gamma_\rho(s)}{\left(s - m_\rho^2\right)^2 + s\Gamma_\rho(s)^2} \Longrightarrow (m_\rho, \Gamma_\rho)$$

ρ spectral function in medium



Leupold et al, Phys.Rev.C58:2939-2957,1998

QCDSR-allowed (Γ,m) at saturation density

free ρ meson

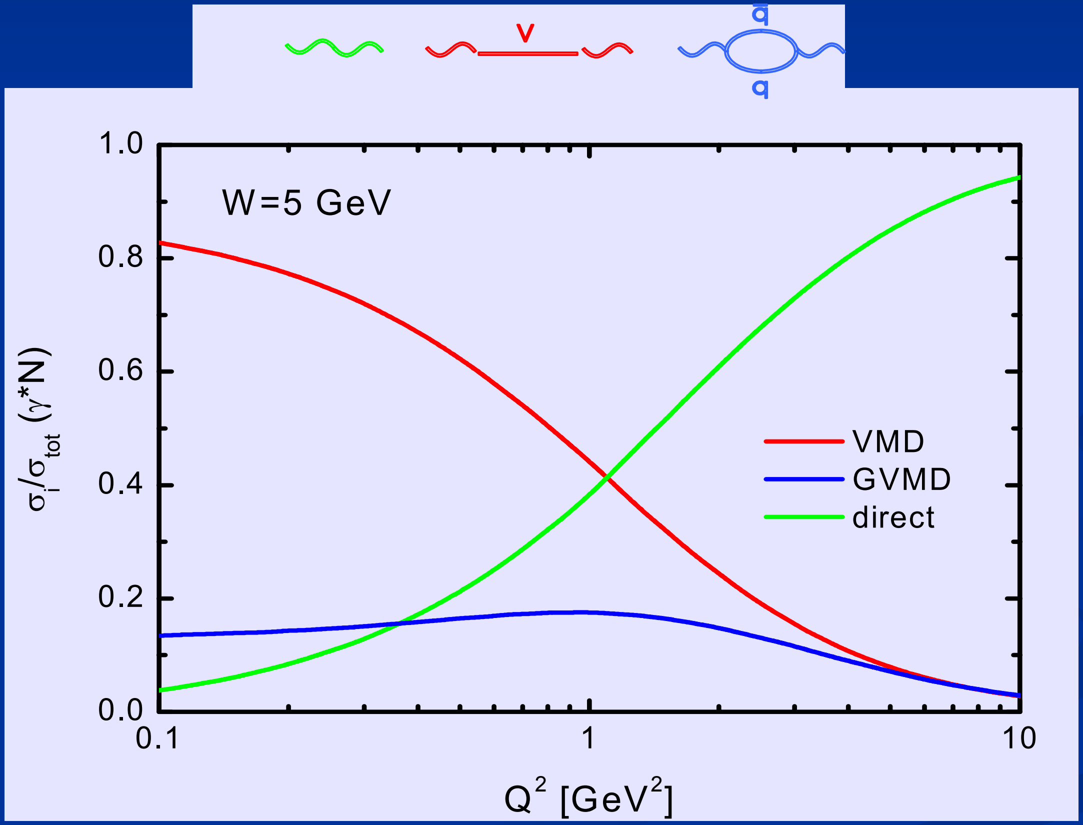
QCD Sum Rules provide constraints for, but do not fix in-medium hadron props

Theoretical Method

- Entrance Channel:
  - Quantum Coherence: Shadowing
- Primary Production
  - Resonance Decay or String-Fragmentation (PYTHIA)
- Exit Channel:
  - Incoherent Final State Interactions (Absorption + Scattering + Side-Feeding), Propagation with self-energies and interactions through resonances or fragmentation

Theoretical Method:
Coherence in Entrance Channel

- Hadronic Structure of the Photon

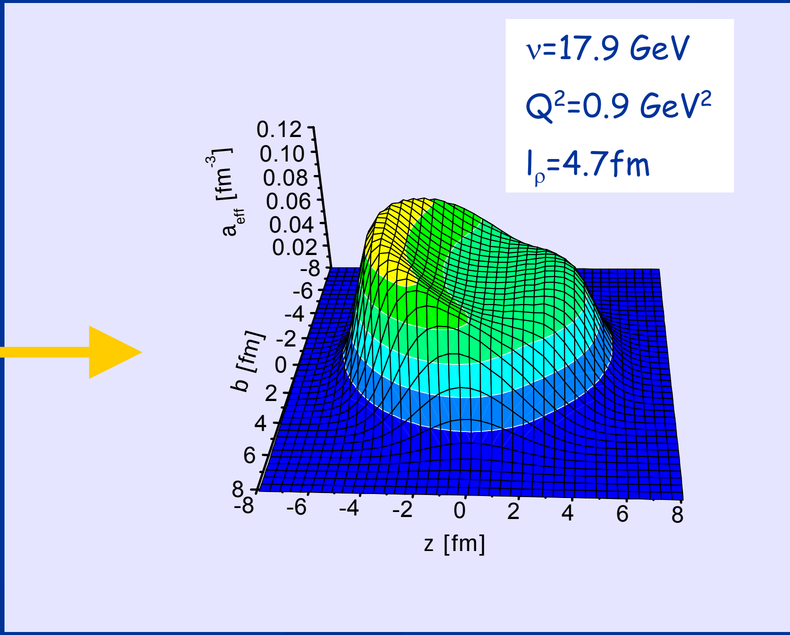


Theoretical Method:
Coherence in Entrance Channel

- Coherence Length: $l_\rho = \frac{2\nu}{Q^2 + m_V^2}$
  - Distance that the photon travels as V meson
- Treat by Glauber

Vector Meson Components in the Nucleus Shadowed

γ^*



Theoretical Method:
BUU CC transport model

- Same Code for Same Physics
  - Photonuclear reactions $\gamma + A$
  - Hadronic reactions π,p + A
  - Heavy-ion reactions A + A
- Resonance and Continuum Region treated
  - Resonance Decays from data
  - Continuum Decays from String Fragmentation

Theoretical Method:
BUU CC Transport Model

$$\left(\frac{\partial}{\partial t} + (\nabla_{\vec{p}} H)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H)\nabla_{\vec{p}}\right) f_i(\vec{r},\vec{p},t) = I_{\text{coll}}[f_1,\ldots,f_i,\ldots,f_M]$$

set of BUU equations coupled via I_coll and mean field

f_i : phase space density

H : Hamilton function

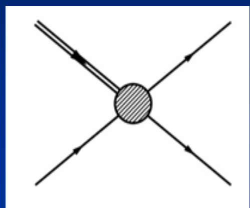
$$H = \sqrt{(\mu + U_s)^2 + \vec{p}^2}$$

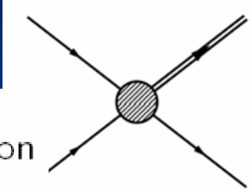
collision integral accounts for changes in f_i due to 2 particle collisions: creation, annihilation, elastic scattering (Pauli blocking for fermions)

1. products of $\gamma^* A$ reaction need not be created in primary $\gamma^* N$ reaction
2. In-medium changes can be modelled in H (selfenergies) and in I_coll (reaction rates, form. times, prehadron cross sections)
3. Experimental acceptance can be simulated event by event

Nucleon-Spectral Functions

$$a(\omega,p) = \frac{\Gamma(\omega,p)}{(\omega - \frac{p^2}{2m_N} - \mathrm{Re}\Sigma(\omega,p))^2 + \frac{1}{4}\Gamma^2(\omega,p)}$$





Assume constant Scattering Amplitude = Short-Range Correlation

$$\Sigma^{>}(\omega,p) = -4i\frac{\overline{|\mathcal{M}|^2}}{(2\pi)^6}\int d\omega_3 \int d\omega_2 \int dp_3\, p_3^2 \int dp_2\, p_2^2 \frac{d\cos\vartheta_2}{p_{\mathrm{tot}}p_3}\int dp_4\, p_4$$
$$\times\, a(\omega_2,p_2)f(\omega_2,p_2)a(\omega_3,p_3)(1-f(\omega_3,p_3))a(\omega_4,p_4)(1-f(\omega_4,p_4))$$

$$\Sigma^{<}(\omega,p) = 4i\frac{\overline{|\mathcal{M}|^2}}{(2\pi)^6}\int d\omega_3 \int d\omega_2 \int dp_3\, p_3^2 \int dp_2\, p_2^2 \int \frac{d\cos\vartheta_2}{p_{\mathrm{tot}}p_3}\int dp_4\, p_4$$
$$\times\, a(\omega_2,p_2)(1-f(\omega_2,p_2))a(\omega_3,p_3)f(\omega_3,p_3)a(\omega_4,p_4)f(\omega_4,p_4)$$

with $p_{\mathrm{tot}} = |\vec{p}+\vec{p}_2|$

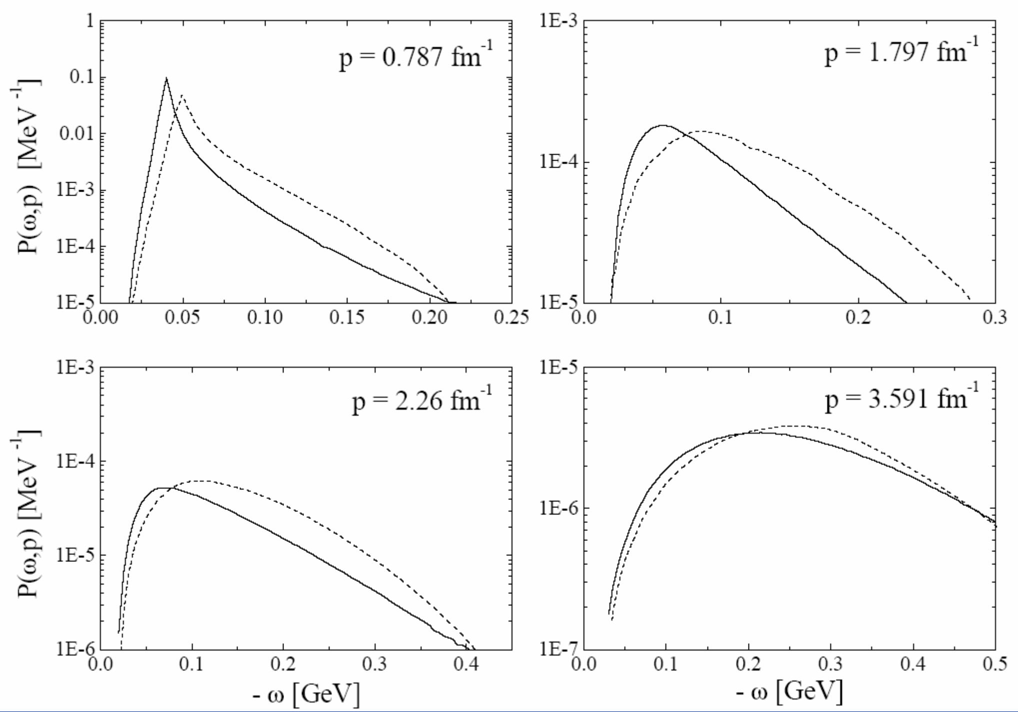
Selfconsistency Problem

$$\Gamma \rightarrow a \rightarrow \Sigma^{<>} \rightarrow \Gamma$$

Collisional Width

$$\Gamma(\omega,p) = 2\,\mathrm{Im}\,\Sigma(\omega,p) = i(\Sigma^{>}(\omega,p) - \Sigma^{<}(\omega,p))$$

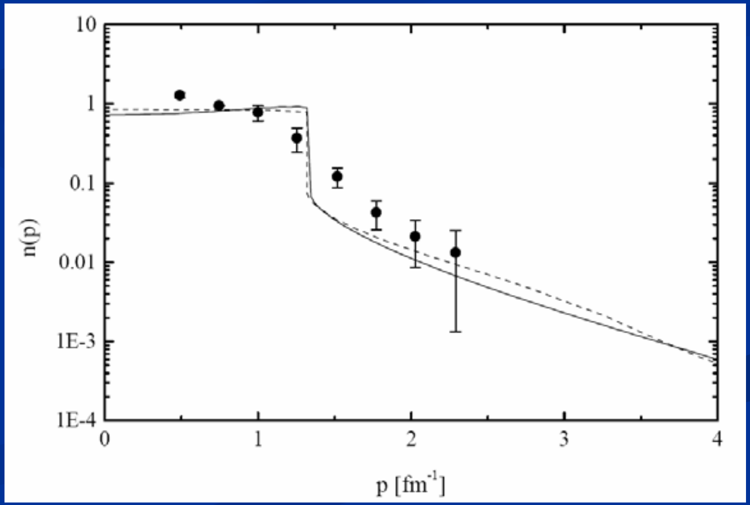
Nucleon-Spectral Functions



Lehr et al, Nucl.Phys.A703:393,2002

--- Benhar et al

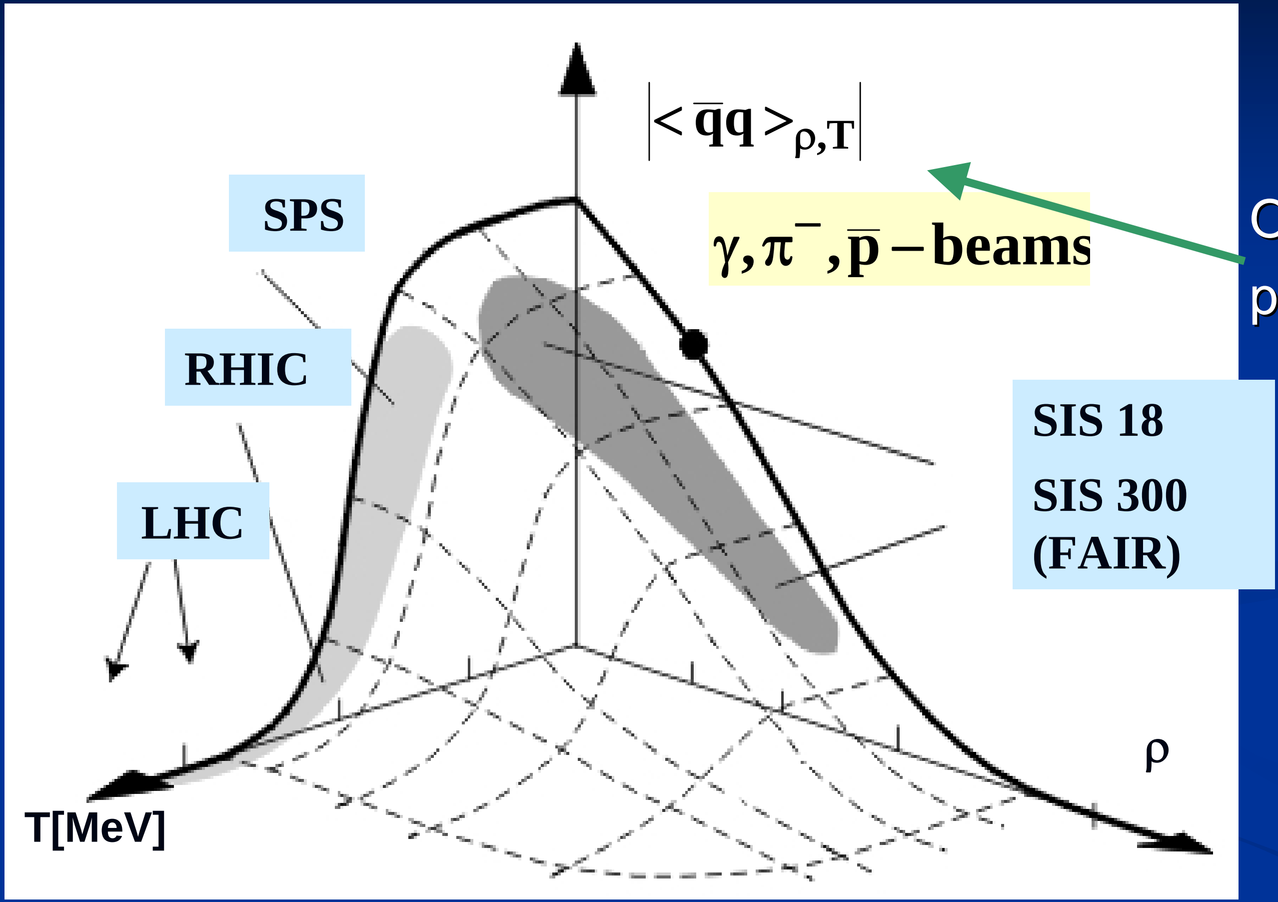
Data: Sick et al



Spectral Functions determined by coll. width

→ Phase space

Chiral Symmetry Restoration



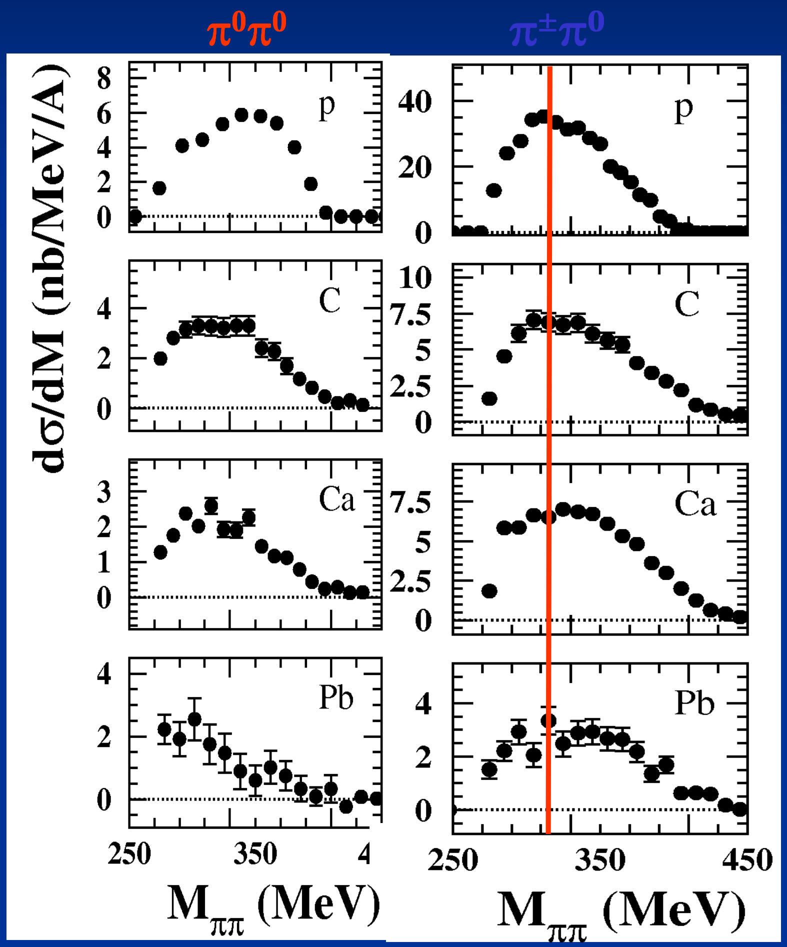
Order parameter

Klimt et al, 1990

Connection to Observables??

Chiral Symmetry Restoration

$2\pi^0$ Production on Nuclei



- Expected:

σ-π degenerate in chiral limit

→ shift of σ strength

to lower masses

TAPS data

E_γ = 400 – 500 MeV

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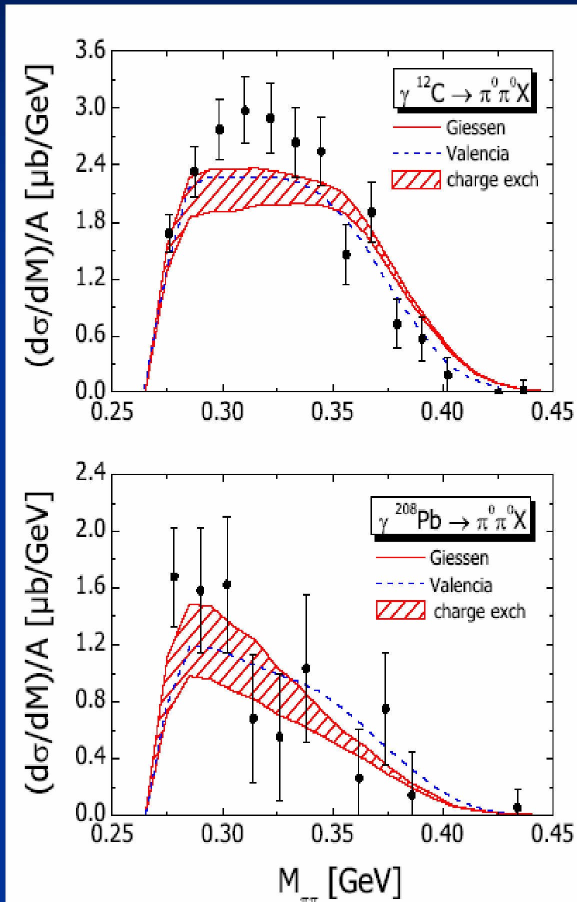
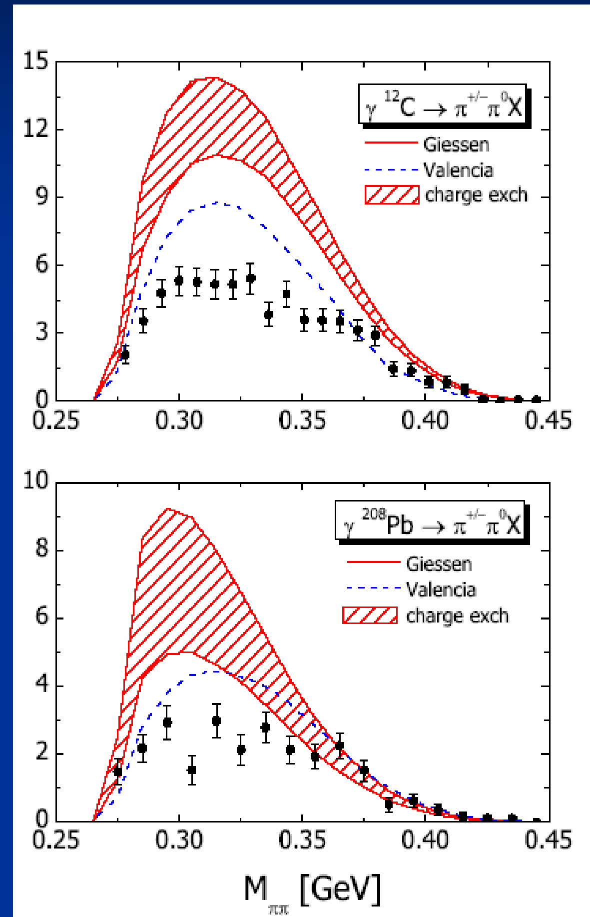
$2\pi^0$ Production on Nuclei





Problem with $\pi^0\pi^{+/-}$ channel

Need: Single $(\gamma,\pi^{\pm})$ data

TAPS Data

Calculations without chiral restoration explain $2\pi0$ data!

P. Muehlich et al, Nucl.Phys.A703:393-408,2002

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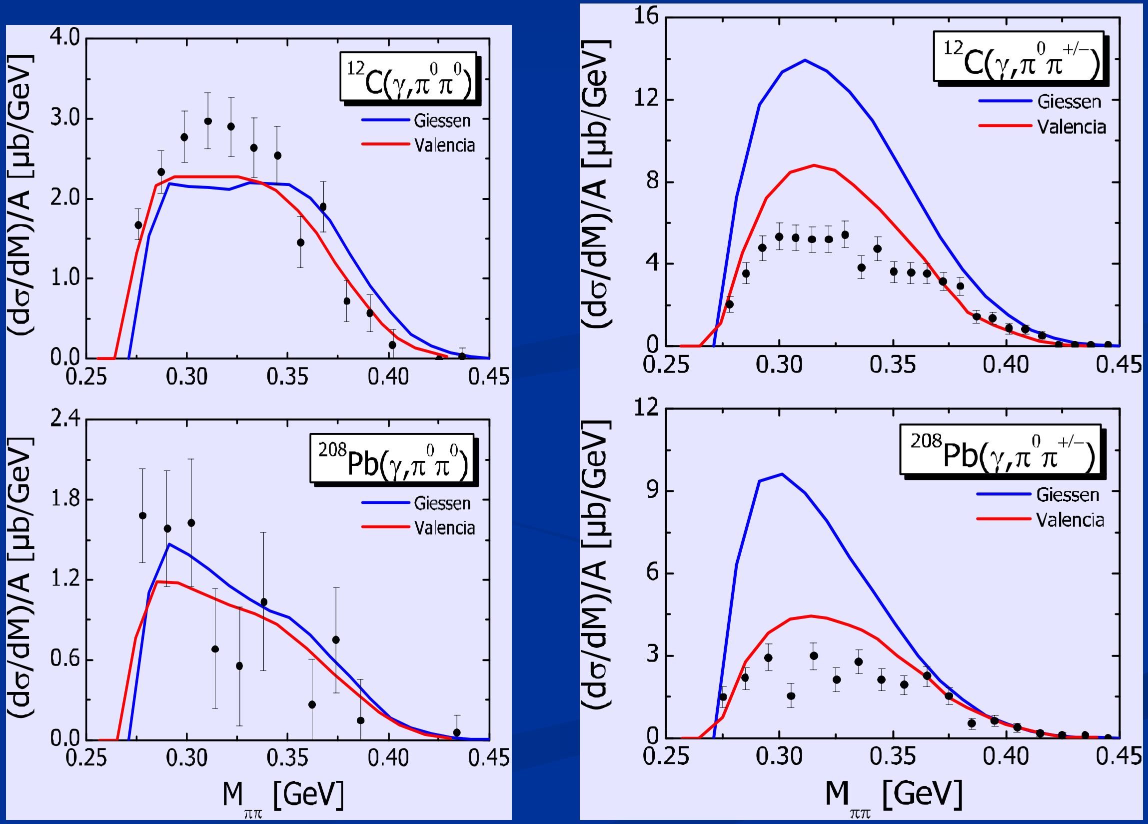
$2\pi^0$ Production on Nuclei

- Chiral symmetry restoration??

  Evidence for lowering of scalar strength in nuclei (??)

  Giessen: only FSI

  Valencia: $\pi\ \pi$ correlation



Need: Hadronic Model

- Propagator in Medium

$$D(\omega, \vec{q}) = \frac{1}{q^2 - m^2 - \Pi_{\text{vac}} - \Pi_{\text{med}}}$$

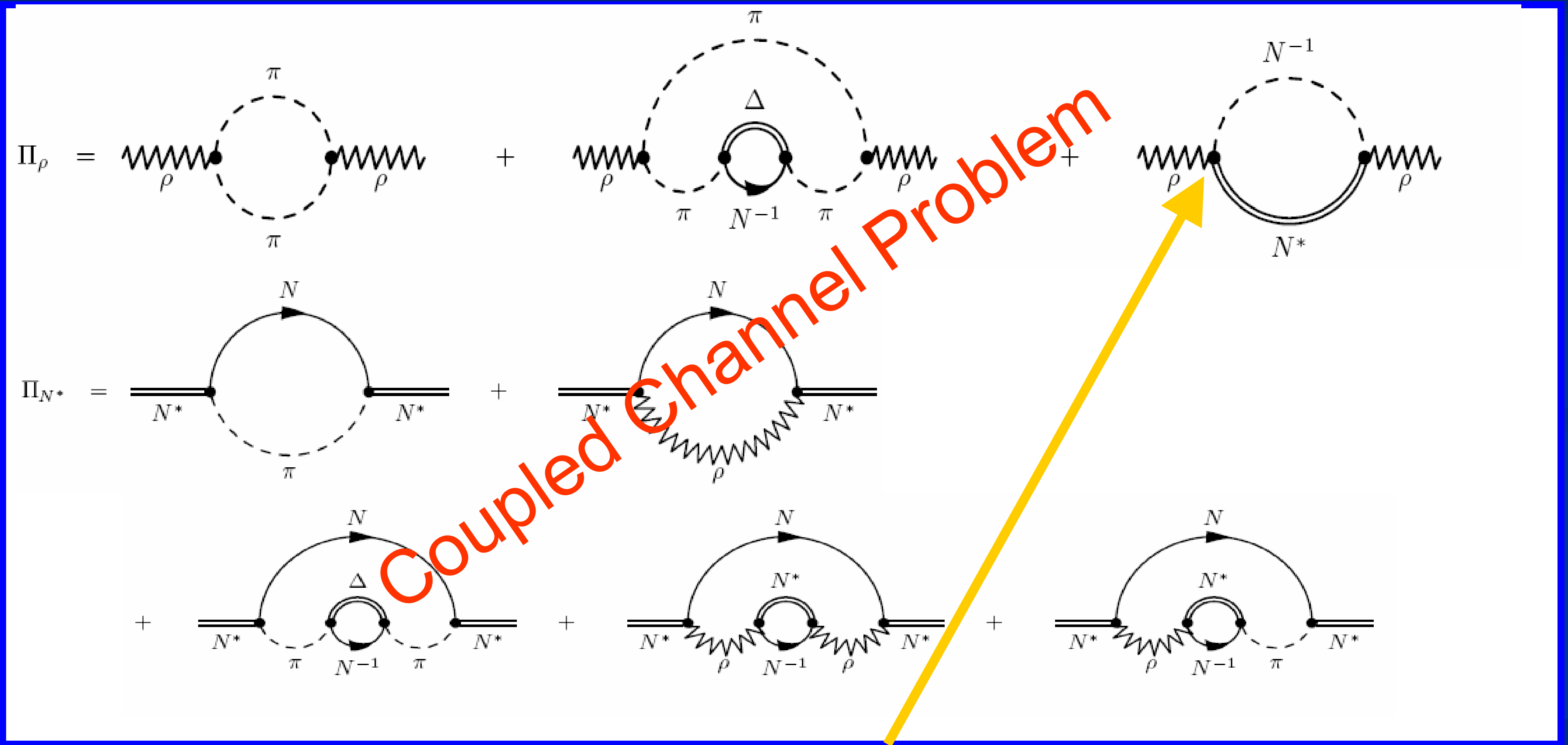
- Low density theorem: $\Pi_{\text{med}} = t\,\rho$

  with (Optical Theorem): $\Im\, t \sim \sigma_{\text{tot}}$

- Mass shift, Collisional broadening:

  $\Delta\, m^2 = \Re\, \Pi_{\text{med}}$ $\Delta\, \Gamma \sim \Im\, \Pi_{\text{med}} \rightarrow v\, \sigma_{\text{tot}} \rho$

ρ and N* selfenergy in medium



Crucial $N^* \to N\,\rho$ coupling

Relevant Resonances: $D_{13}(1520)$, $P_{13}(1720)$

- PDG:
  - $D_{13} : \Gamma_{N\rho} \approx 20\ \%$ subthreshold !
  - $P_{13} : \Gamma_{N\rho} \approx 80\ \%$

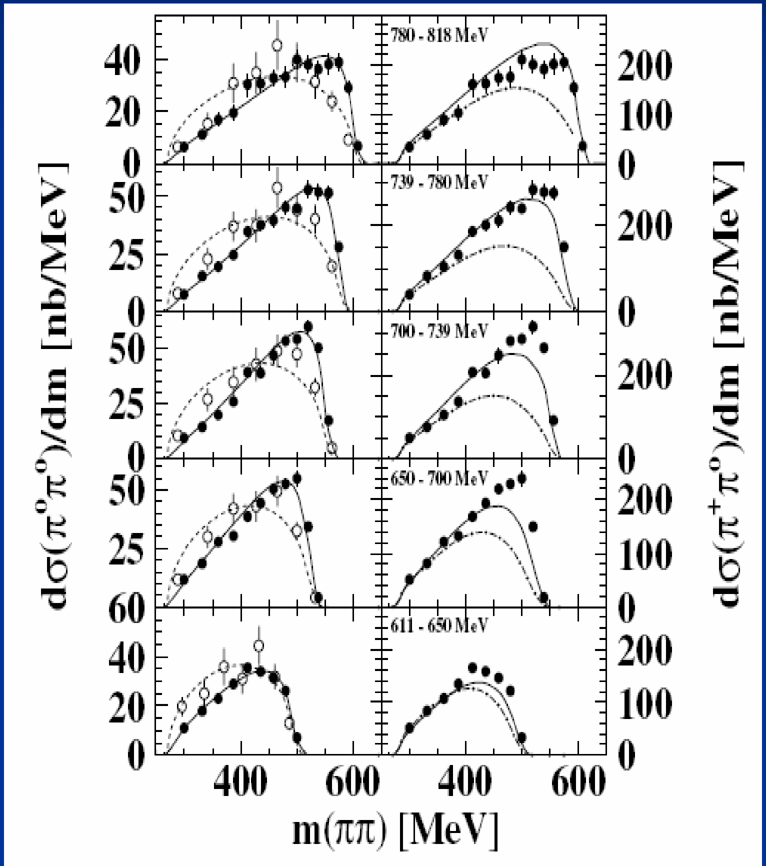
- D_{13} subthreshold ➔ large coupling to $N\rho$

  But: so far not directly been measured!

  Only indirect infos from 2π invariant masses

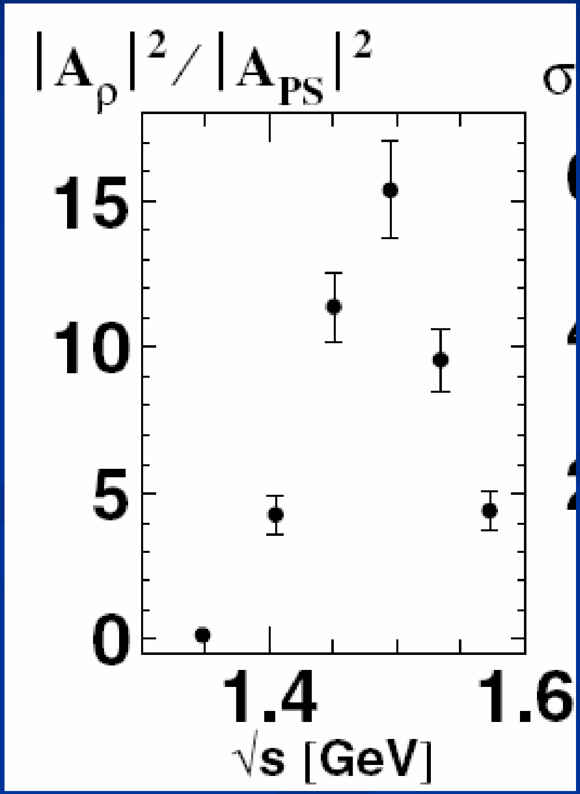
N(1520) → N ρ

Experiments: Daphne, TAPS at MAMI



→

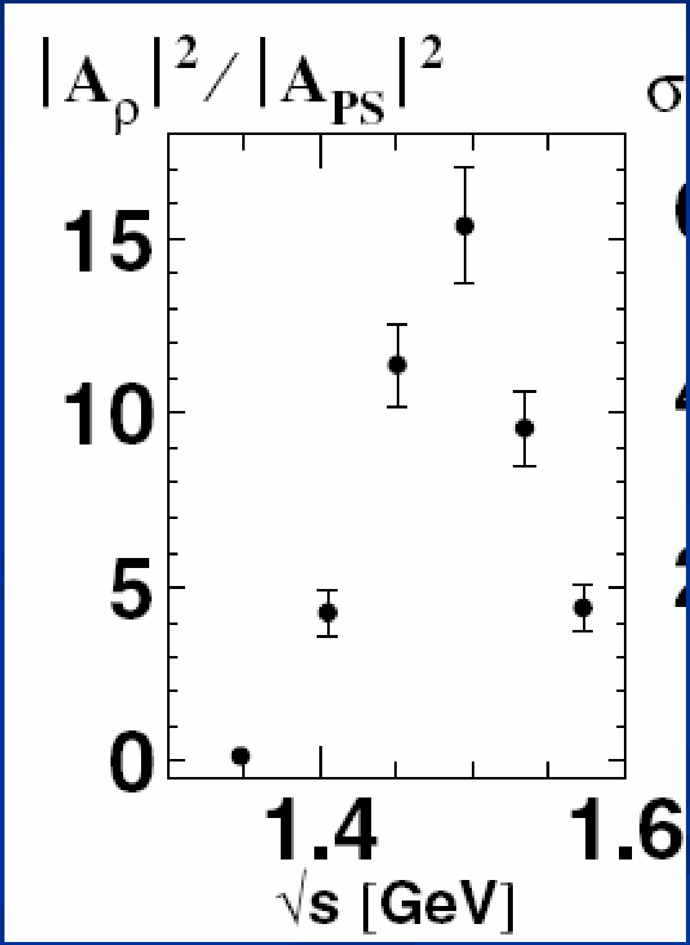
ρ– strength



PWA identification of ρ–meson still missing

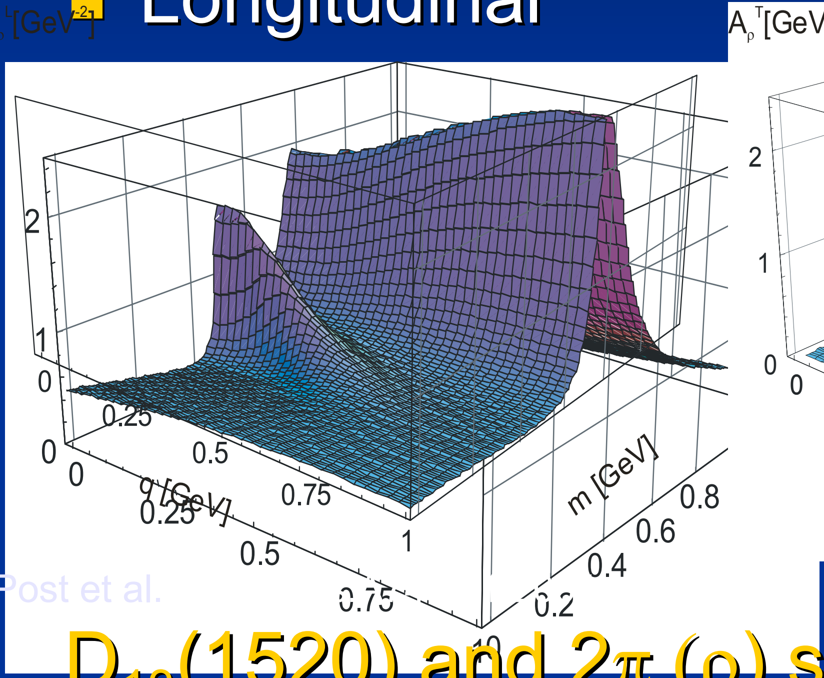
N(1520) → N ρ

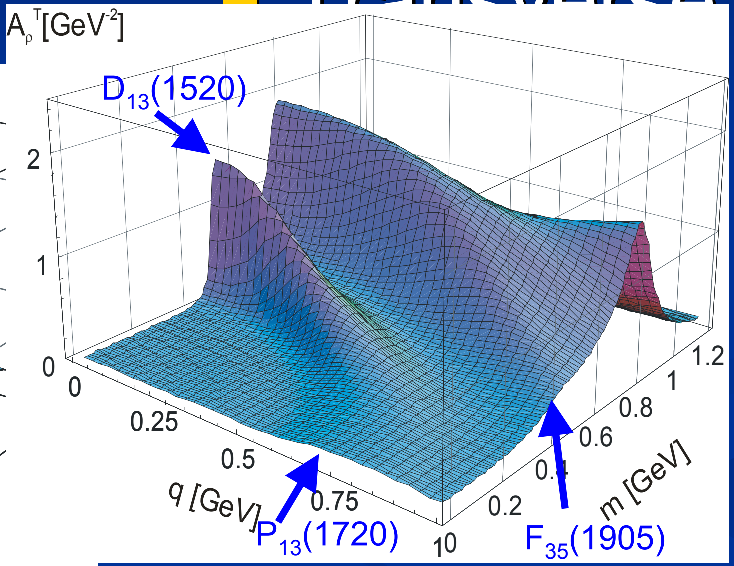
$$\frac{d\sigma}{dm} \sim |a(\sqrt{s}) + b(\sqrt{s})p_\pi(m_{\pi\pi}) \cdot D_\rho(m_{\pi\pi})|^2 P_{\sqrt{s}\rightarrow\pi\pi N} ,$$



Rho meson in matter

- Longitudinal
- Transverse



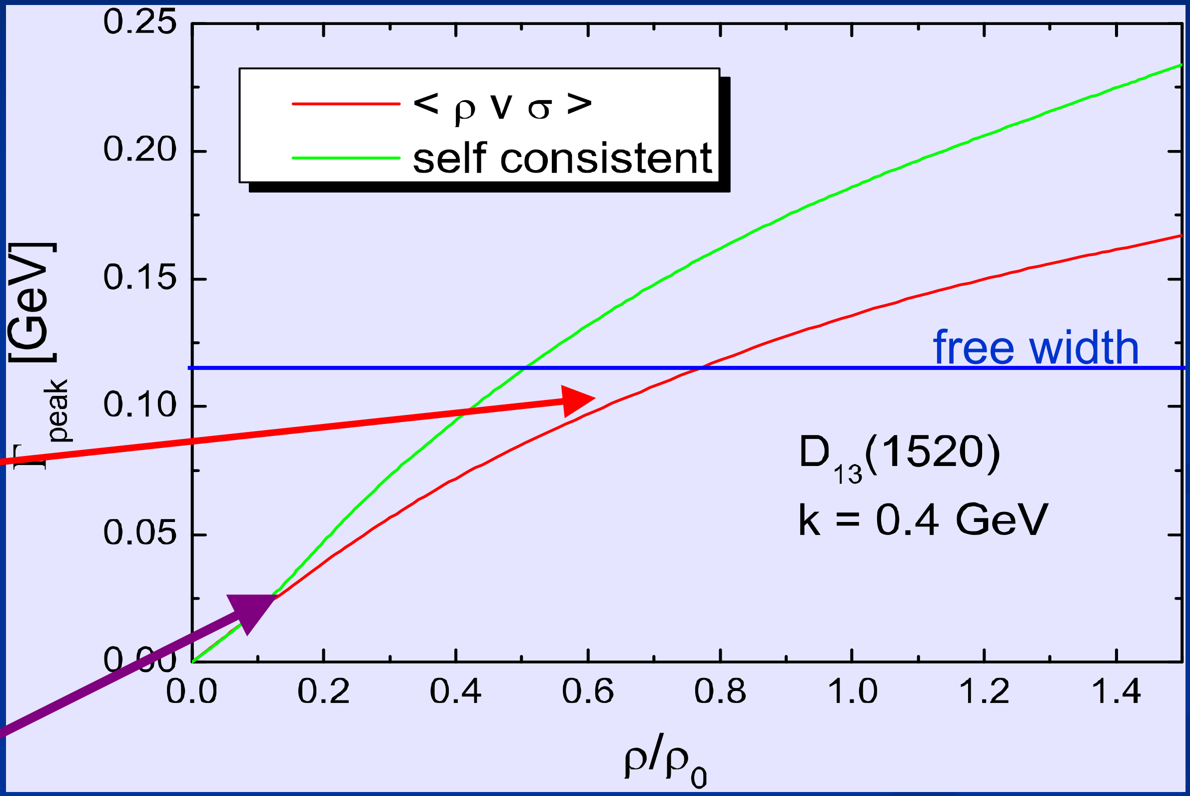


Post et al.

D_{13}(1520) and 2π (ρ) strongly mixed

In-medium Resonance D13(1520)

Collision width: N(1520) doubles width!



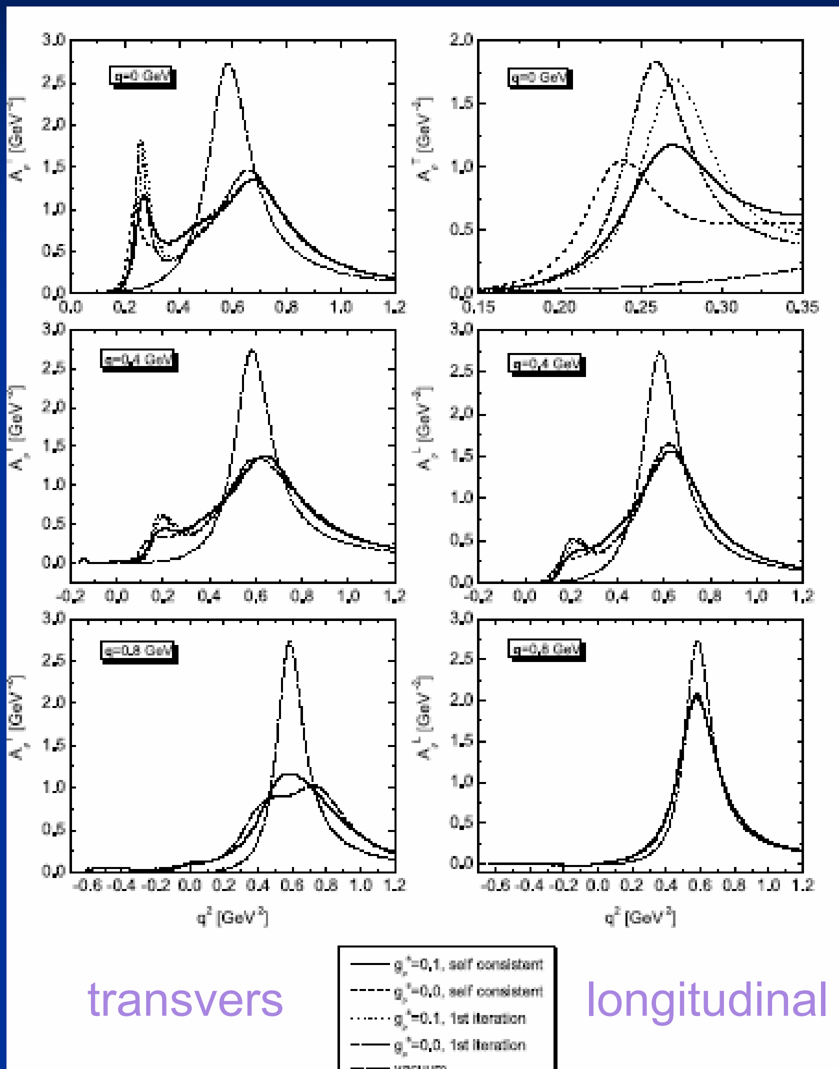
t-ρ approximation

fails already at very low density

Solves photoabsorption puzzle?

Post et al, Nucl.Phys.A741:81,2004

In-medium Resonance N(1520)

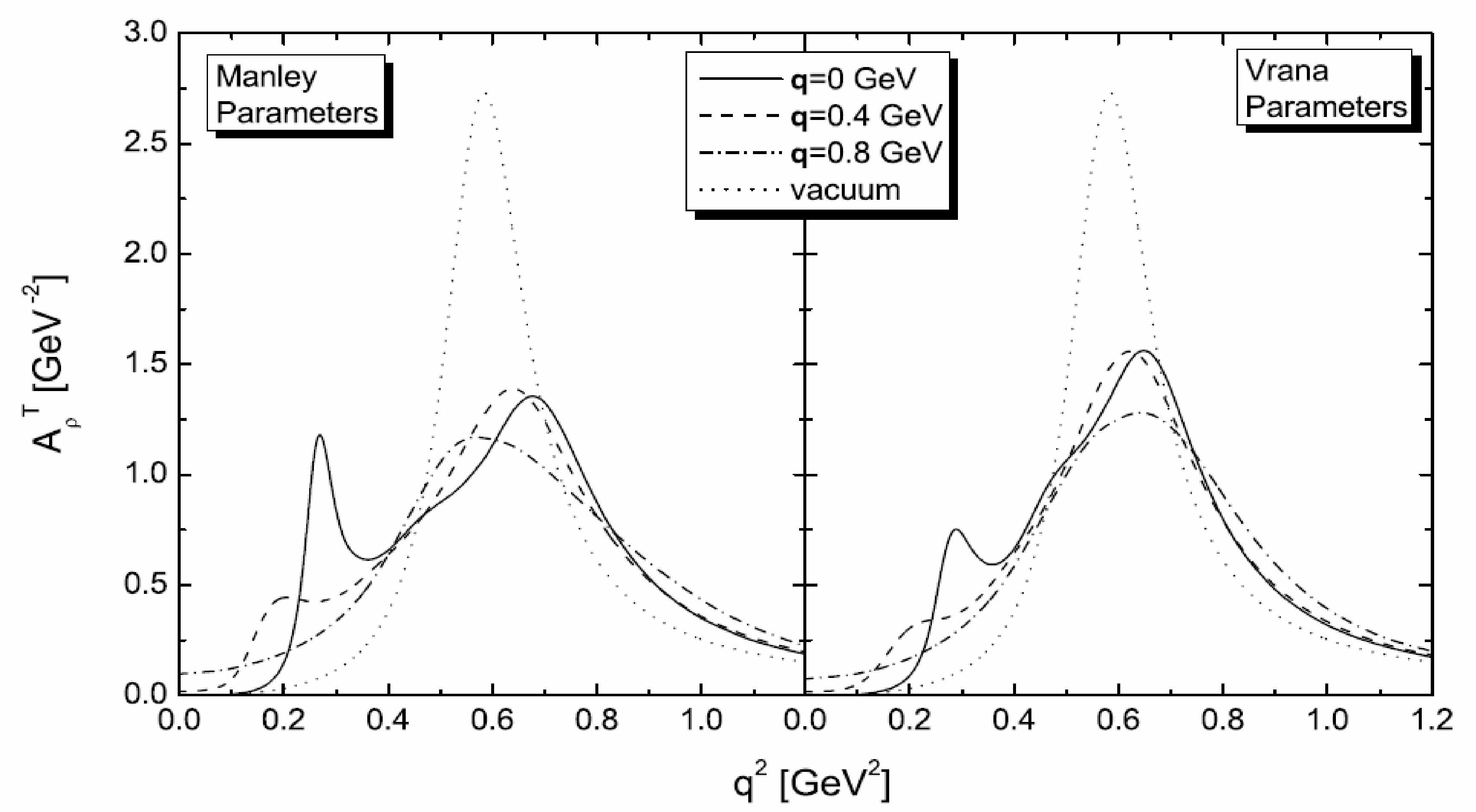


Double bump from s-wave coupling to D13(1520)

D13 influence reduced, p-wave coupling to P13(1720) and F35(1905)

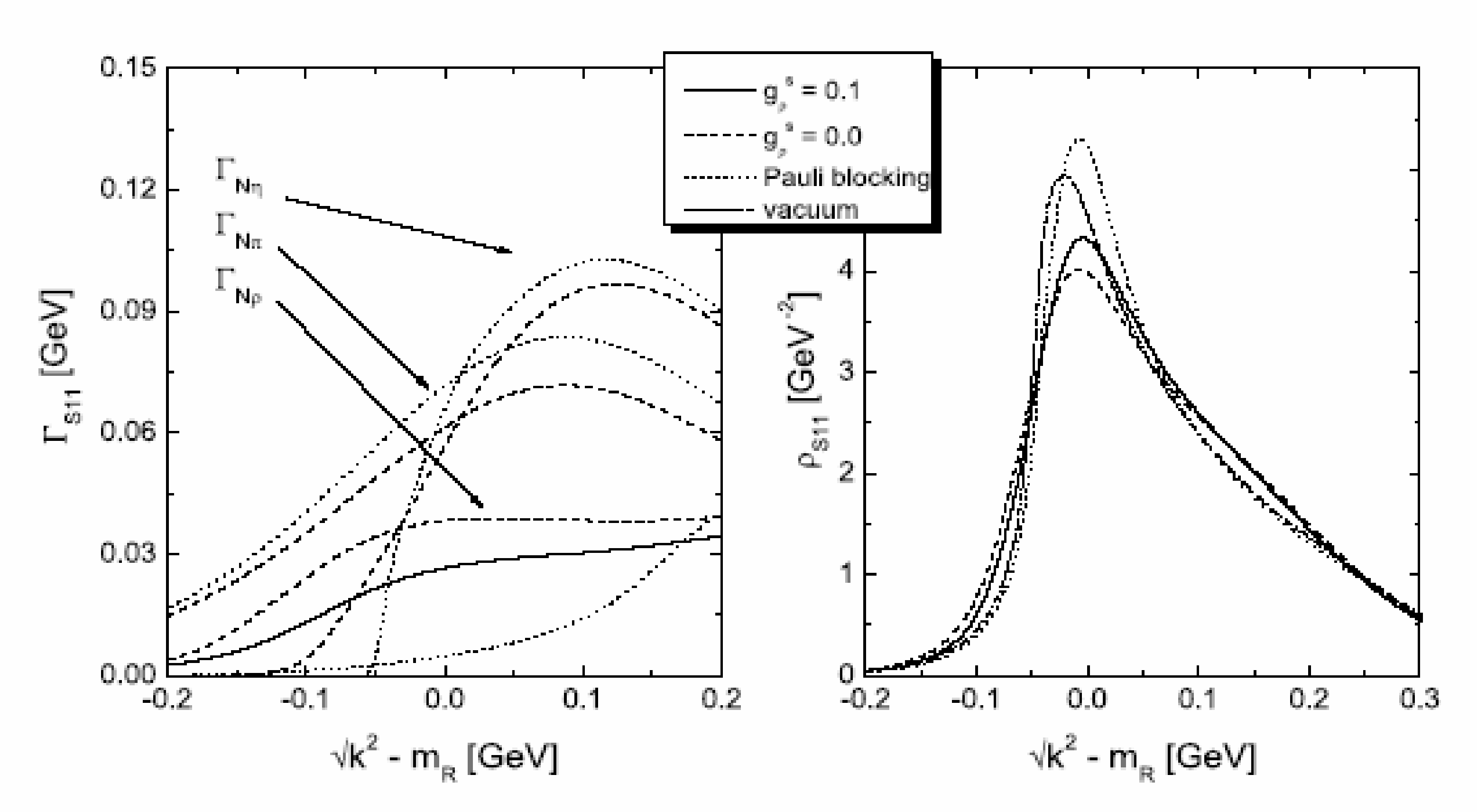
Transverse broadened by coupling to higher resonances
Longitudinal does not couple to p-waves, only weakly to s-waves at large q

In-medium Resonance D13(1520)
parameter-sensitivity



Post et al, Nucl.Phys.A741:81,2004

In-medium Resonance S11(1535)



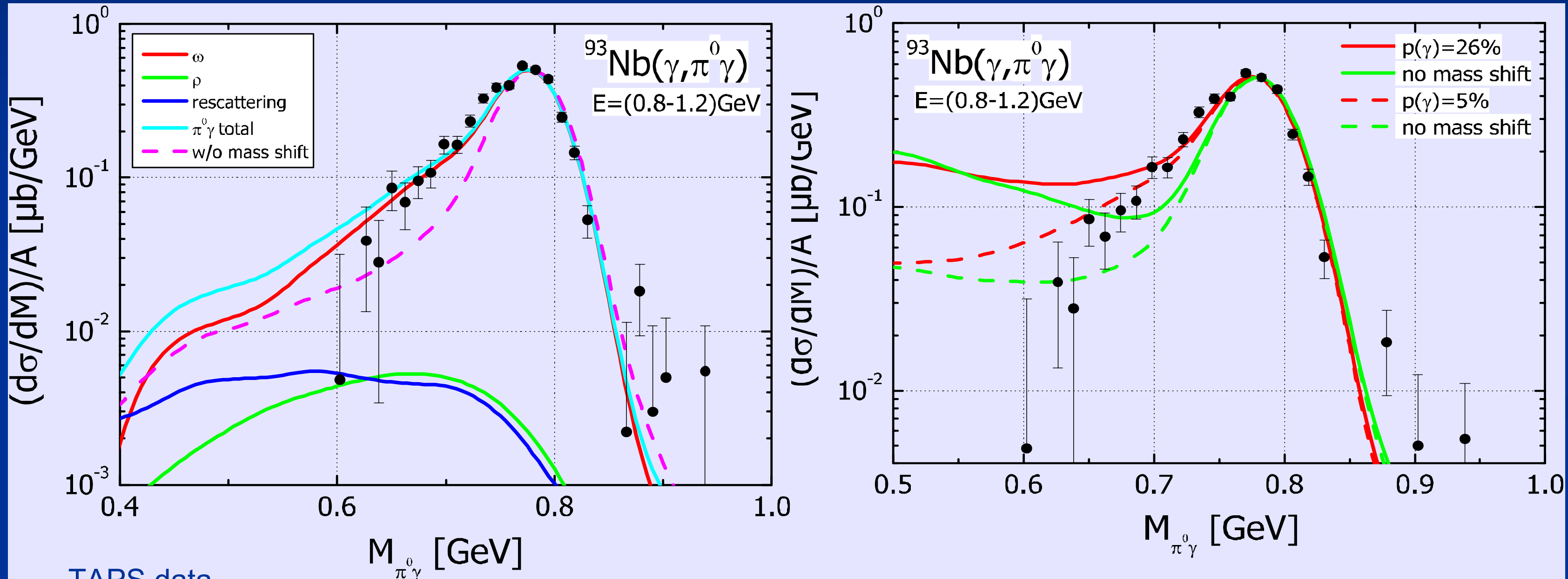
Post et al, Nucl.Phys.A741:81,2004

S11(1535) only little modified

Largest changes from Pauli block and mod. ρ spectral function

Omega in Medium

- $\omega \to \gamma\ \pi^0$ (TAPS@ELSA)



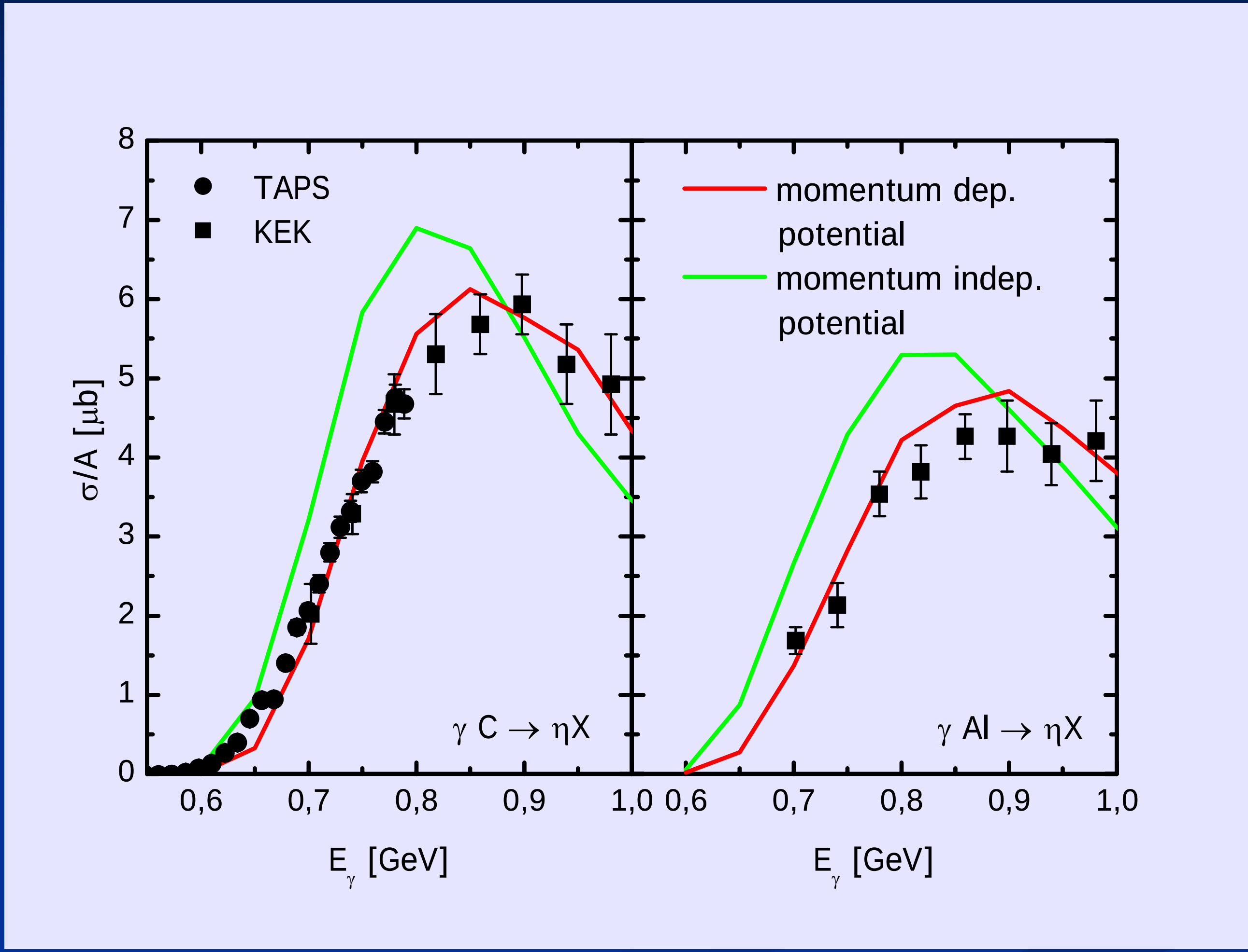
TAPS data

$M_\omega = M_\omega^0\ (\ 1 - 0.16\ \rho/\rho_0)$
$\Gamma_\omega \approx 40$ MeV at ρ_0 and p_ω=0
M independent of p_ω

Background from
$2\pi^0 \to 4\ \gamma$,
one escapes with $p(\gamma)$

η Photo-Production on nuclei

- S11(1535): small in-medium change for p=0, sizeable momentum dependence of self-energy.

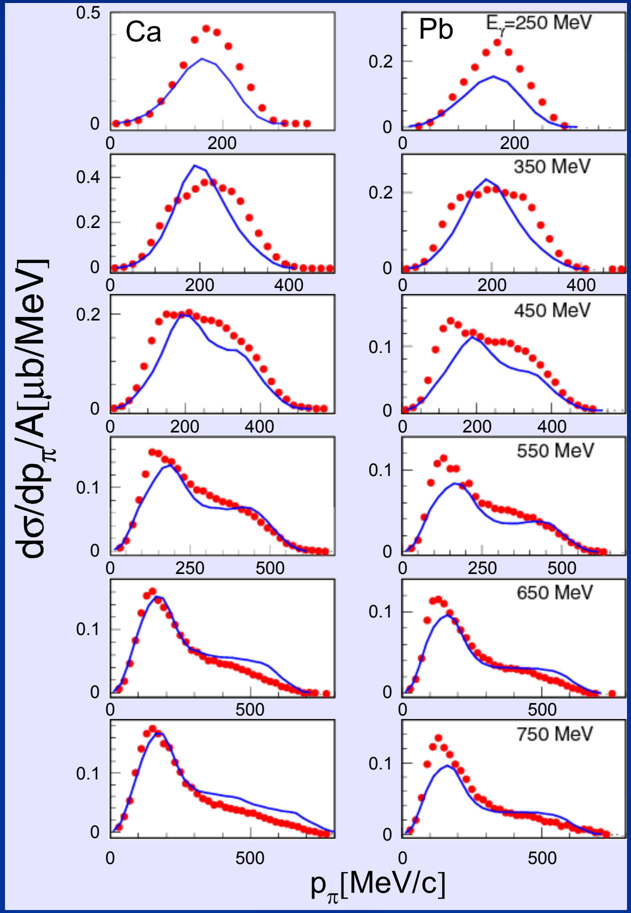


J. Lehr et al, Phys.Rev.C68:044601,2003

Photo-pion production on nuclei

TAPS Data on π^0 production (Krusche et al)

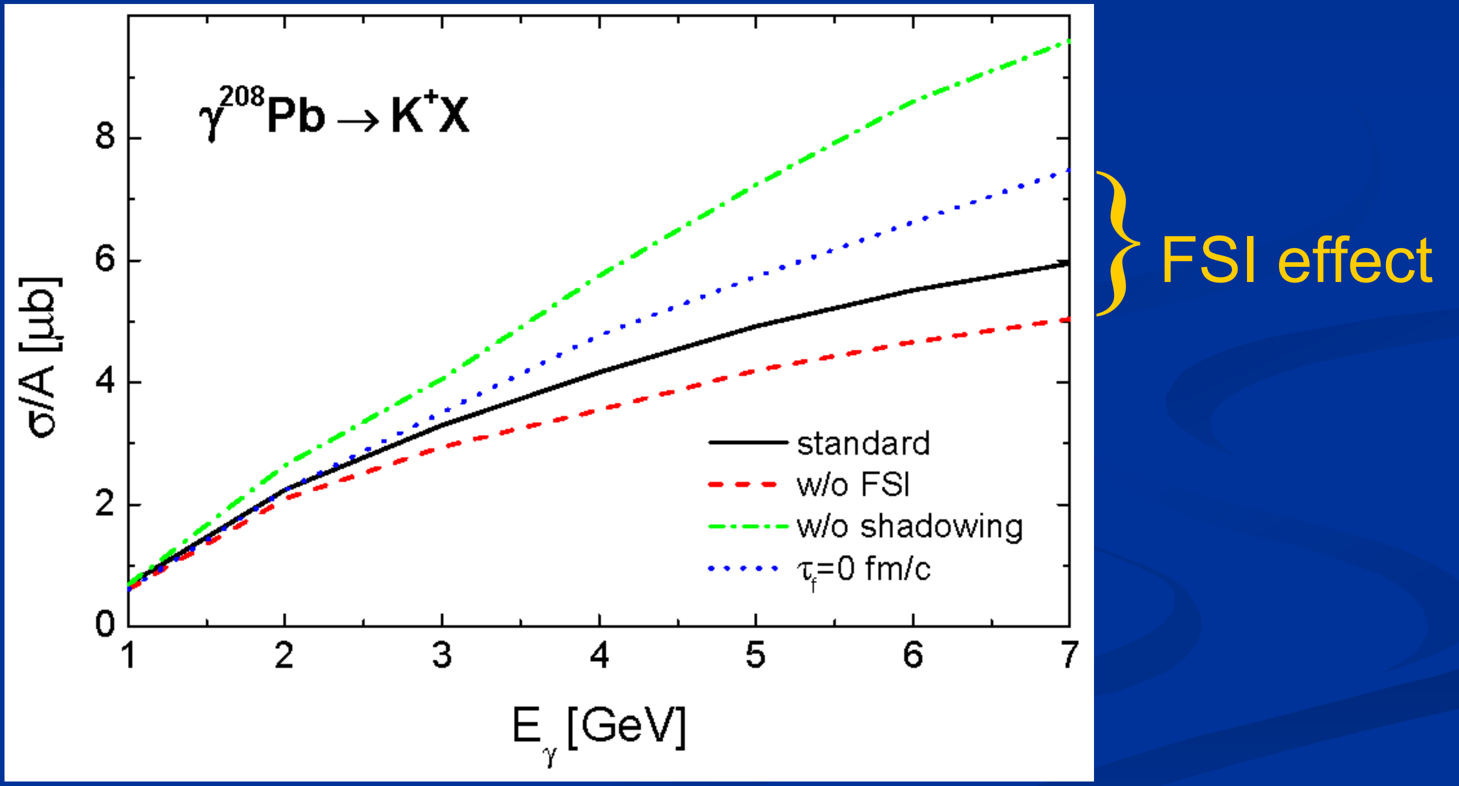
Theory:
Lehr et al



From:
Krusche et al, nucl-ex/0406002

Coupled Channel Effects

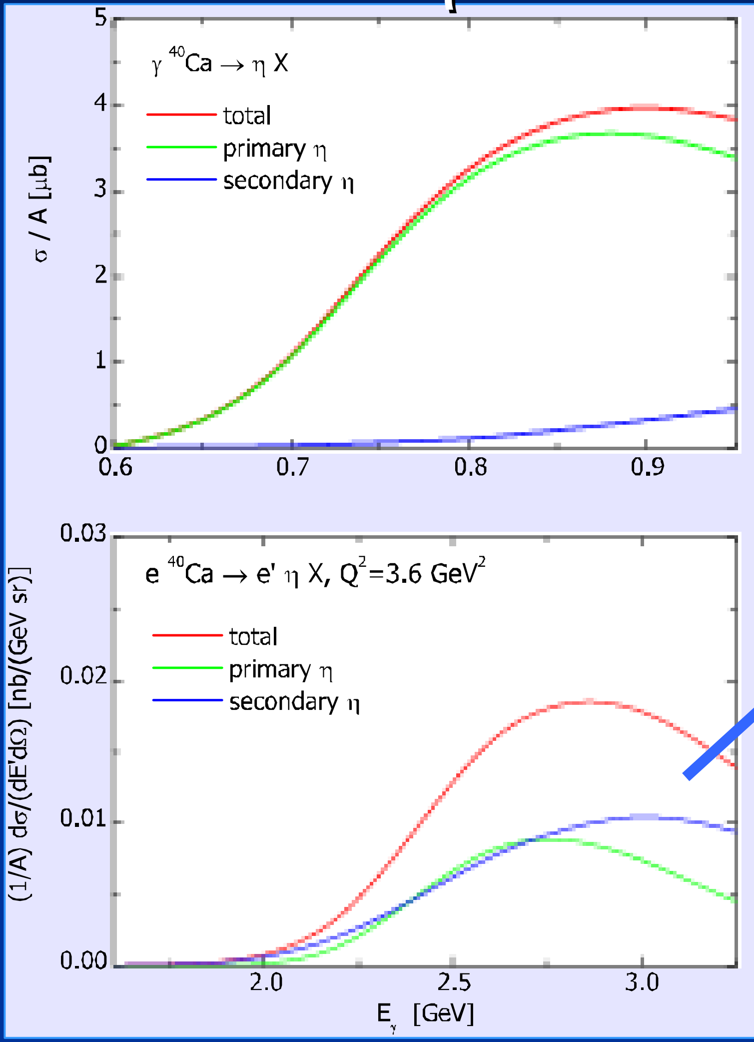
- Final state interactions can increase cross section



Falter et al

Coupled Channel Effects

η Electroproduction



Secondaries

Lehr et al, PRC68:044603,2003

$\gamma N \to \pi N, \pi N \to \eta N$

Dominate

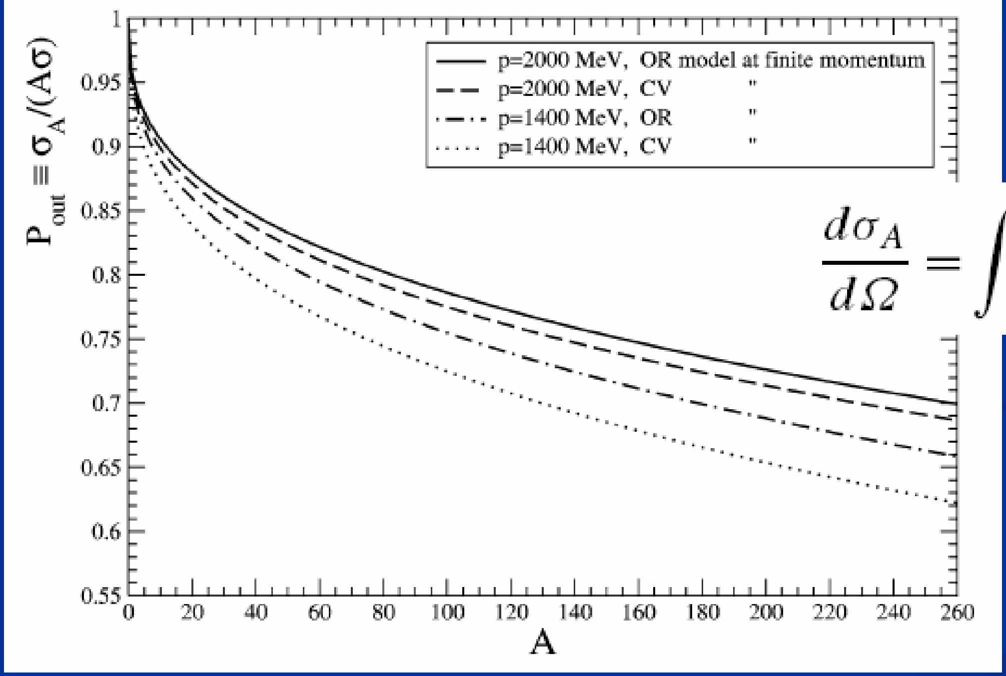
Coupled channel treatment necessary !

ϕ photoproduction (Spring 8)

- Predicted:
  - $\Delta m \approx -30$ MeV
  - $\Gamma_{coll} \approx 24$ MeV
- Problem:
  - Strong FSI on kaons ($\phi \rightarrow K^+K^-$)
  - Coulomb effects on kaons
  - In-medium self-energies of kaons

ϕ photoproduction (Spring 8)

- Integral test: $\Im(\Pi)$ through absorption length (Glauber)➔ A-dependence

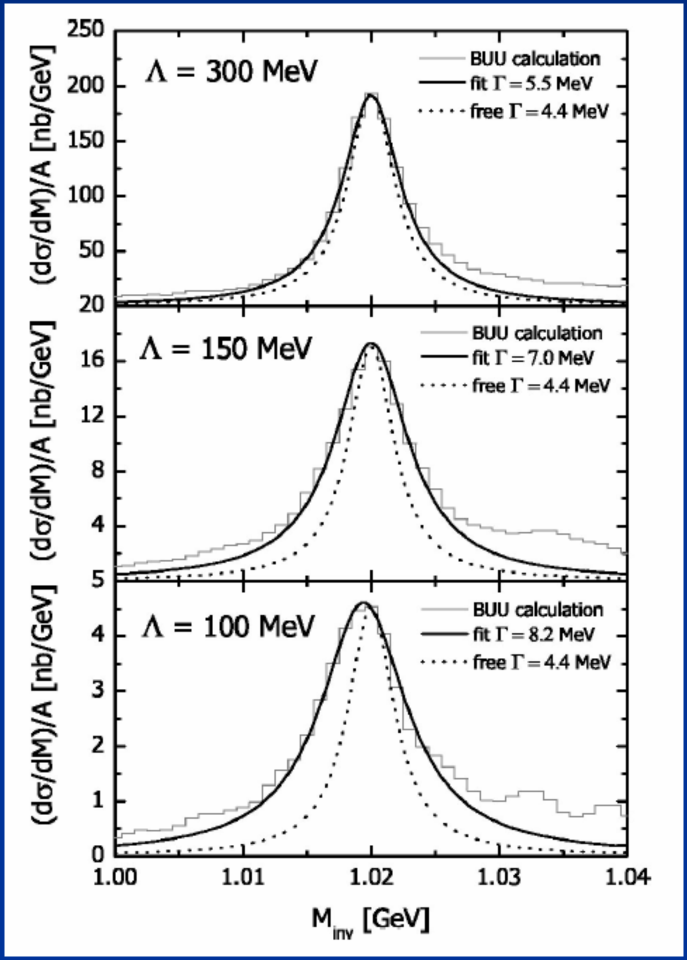


Cabrera et al, Poster

$$\frac{d\sigma_A}{d\Omega} = \int d^3\vec{r}\,\rho(r)\,\frac{d\sigma}{d\Omega}\,e^{-\int_0^\infty dl\,\frac{-1}{p}\,\mathrm{Im}\,\Pi(p,\rho(r'))}$$

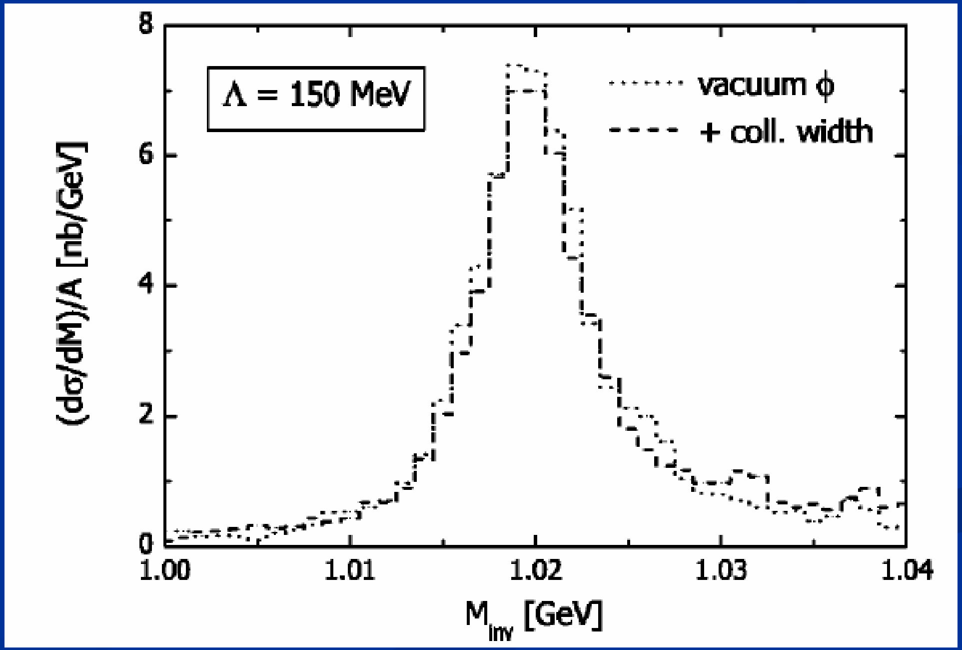
ϕ photoproduction (Spring 8)

Muehlich et al, Phys.Rev.C67:024605,2003



Collisional broadening ≈ × 2

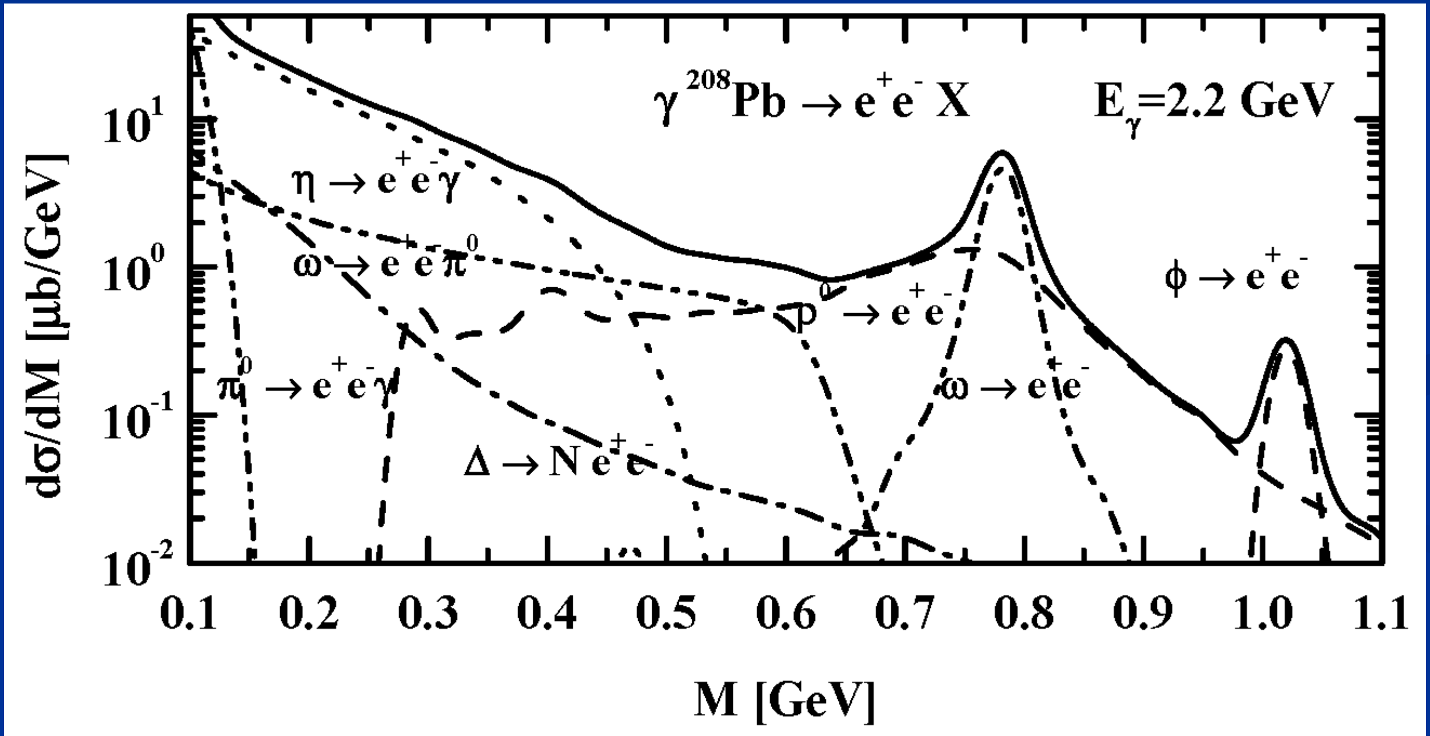
But: Coulomb kills it all



Dileptons: light from the interior

- JLab Experiment E-01-112, g-7

(Djalali, Weygand, Tur et al.)



Same sources as in URHICs!

Dileptons: light from the interior

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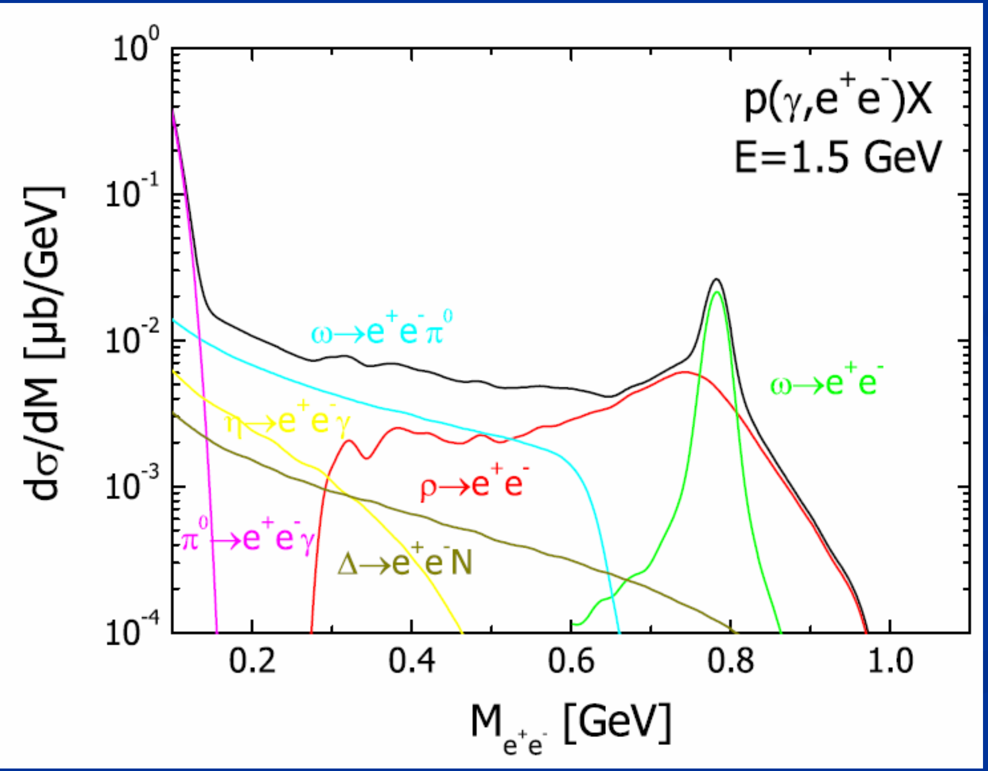
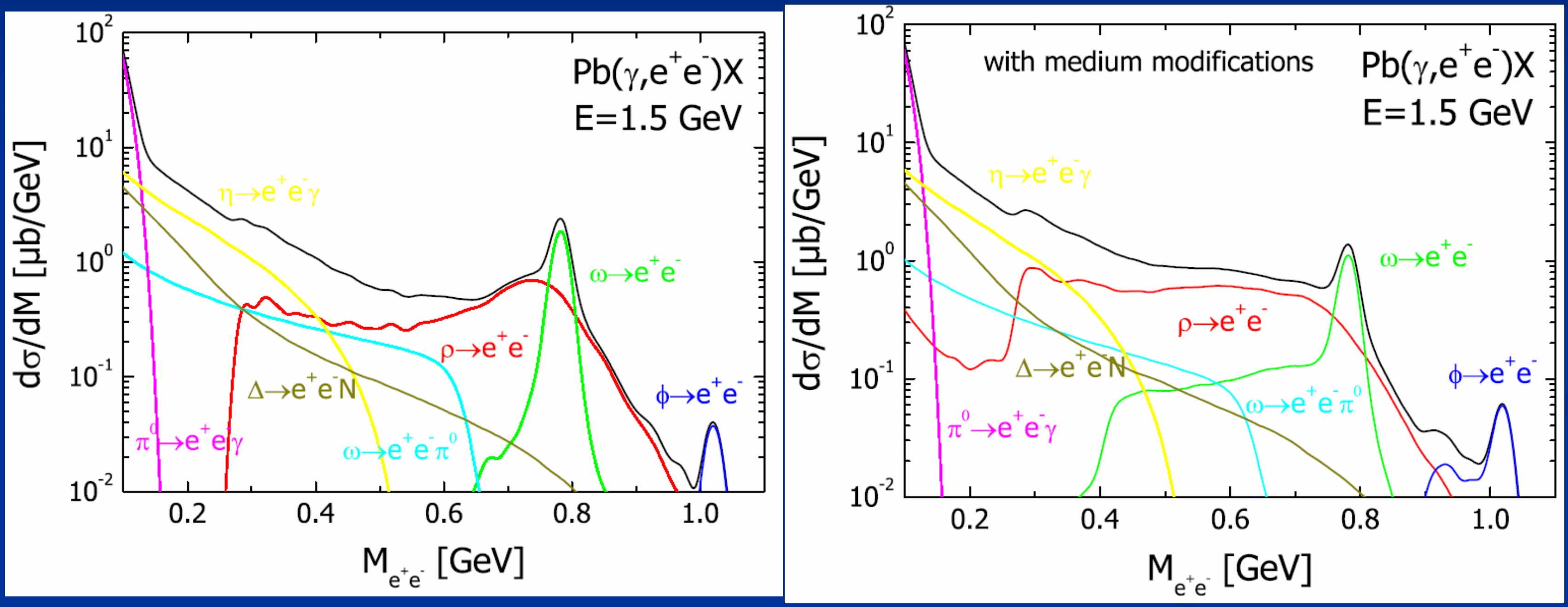


$\gamma + p \rightarrow p + e^+e^-$

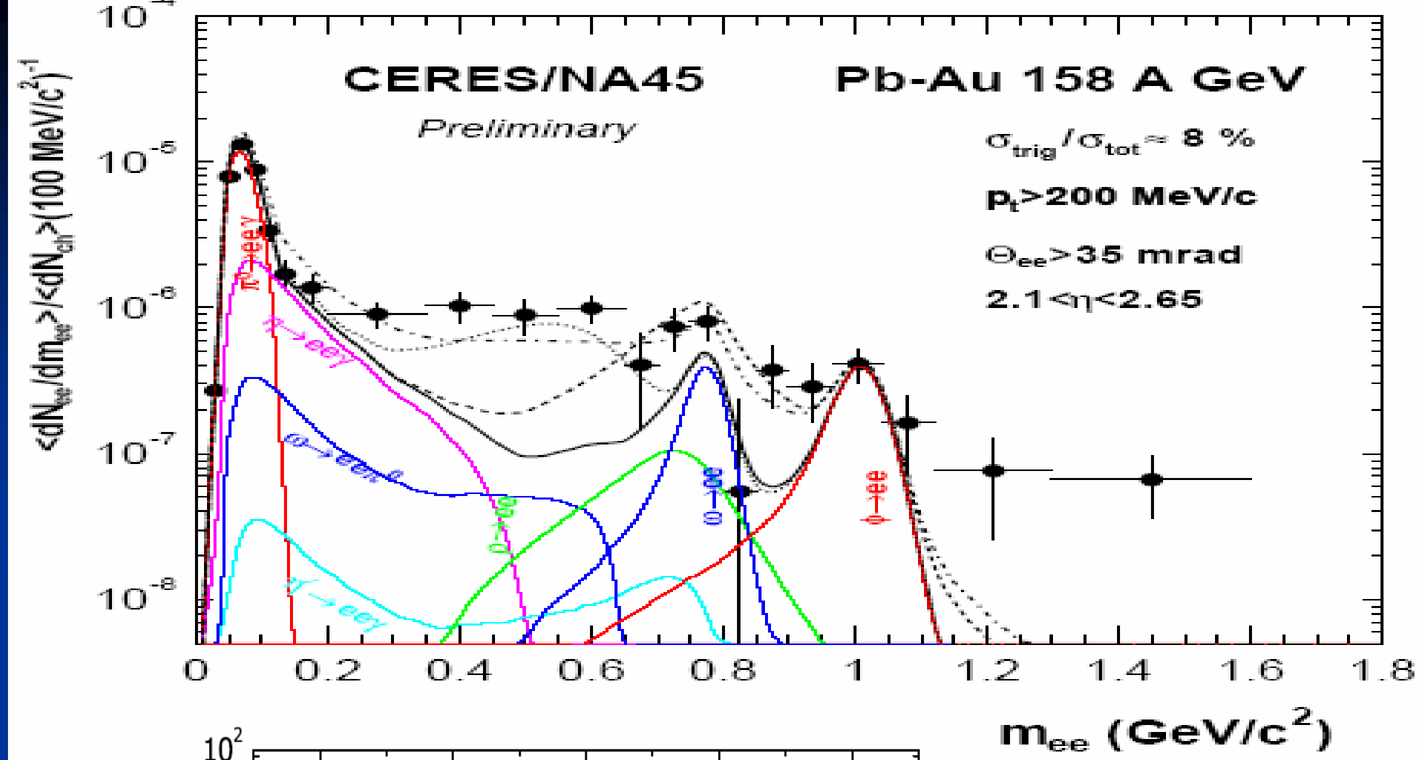
gives access to em formfactor in time-like region

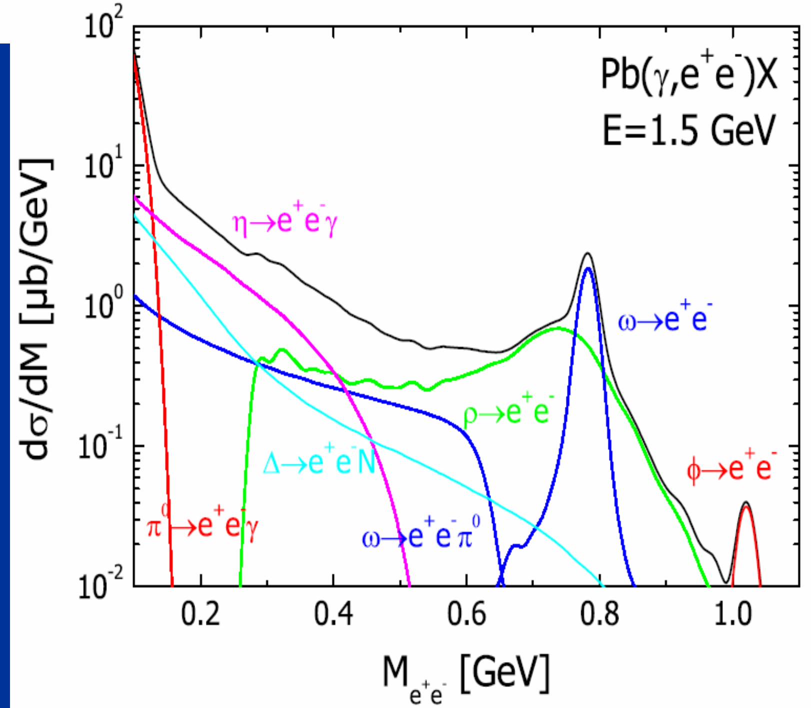
JLab Experiment E-01-112, g-7
(Djalali, Weygand, Tur et al.)



M. Effenberger et al, Phys.Rev.C60:044614,**1999**

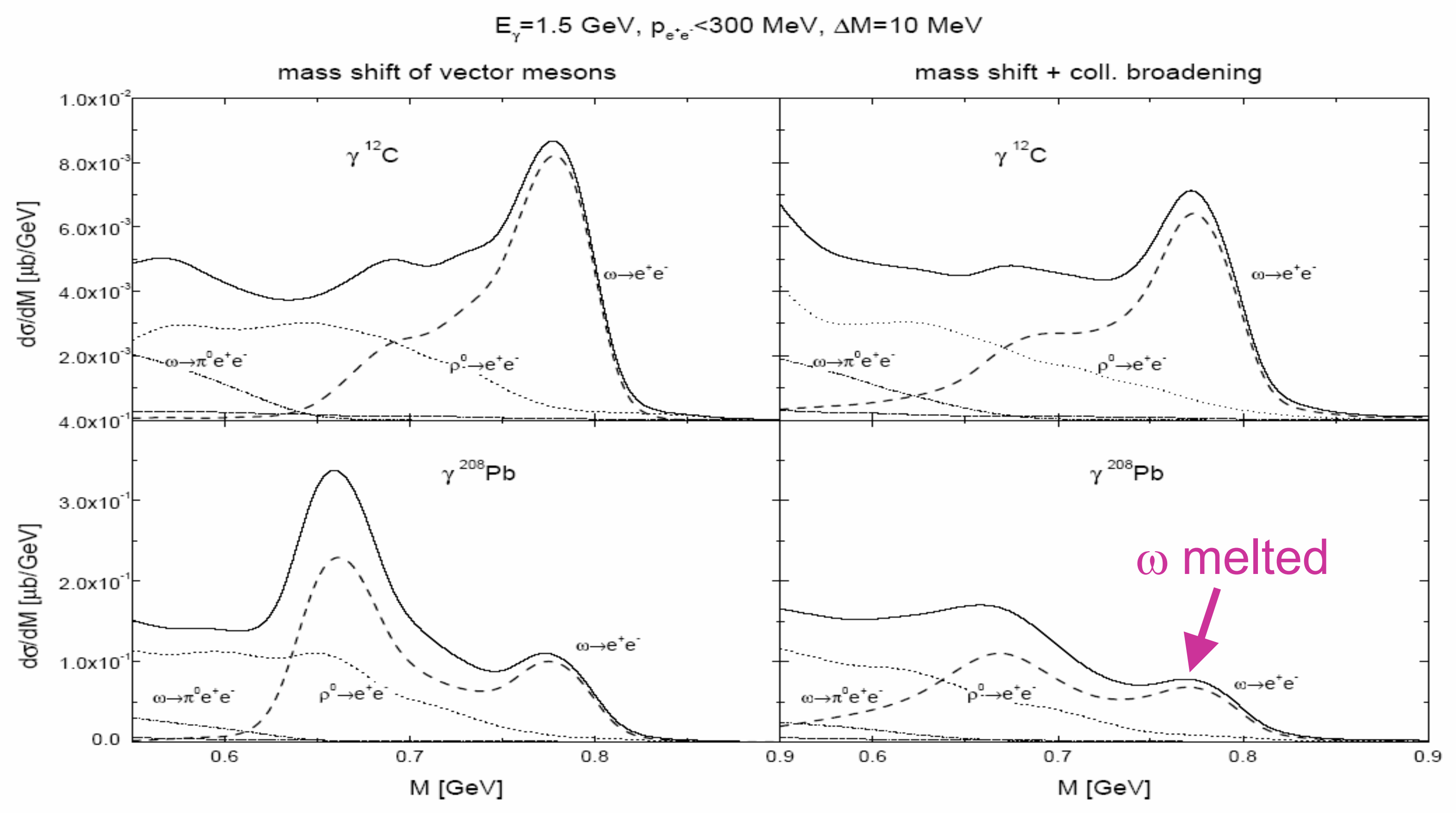
Same sources as in URHICs!





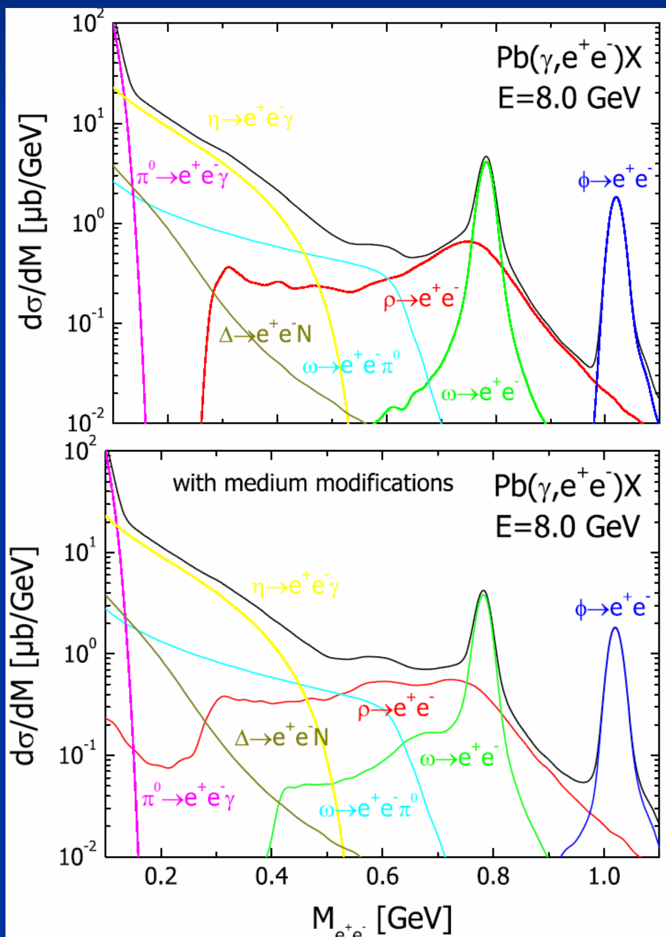
Same Sources !

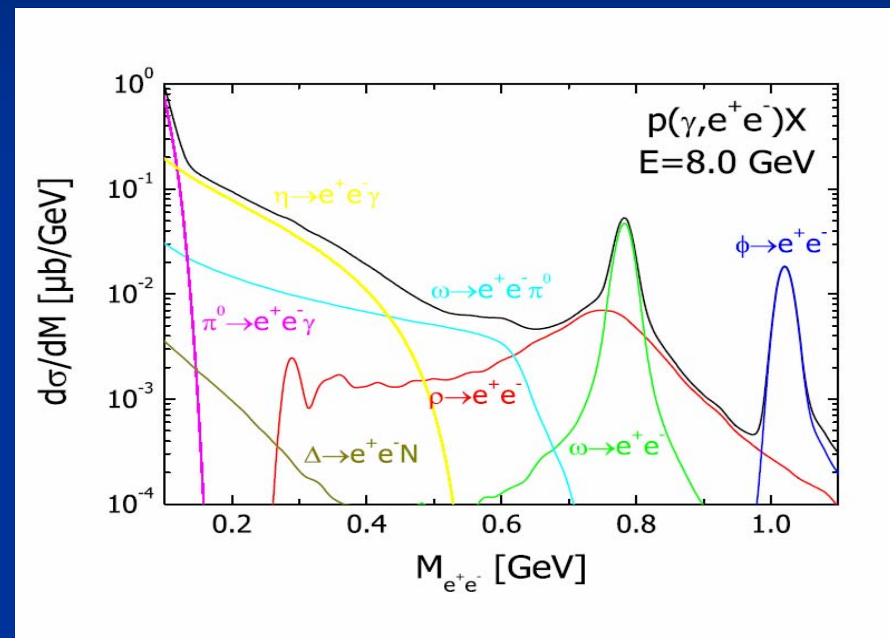
Dileptons: light from the interior



ω peak fades away with A with cut on low momenta

Dileptons at 8 GeV



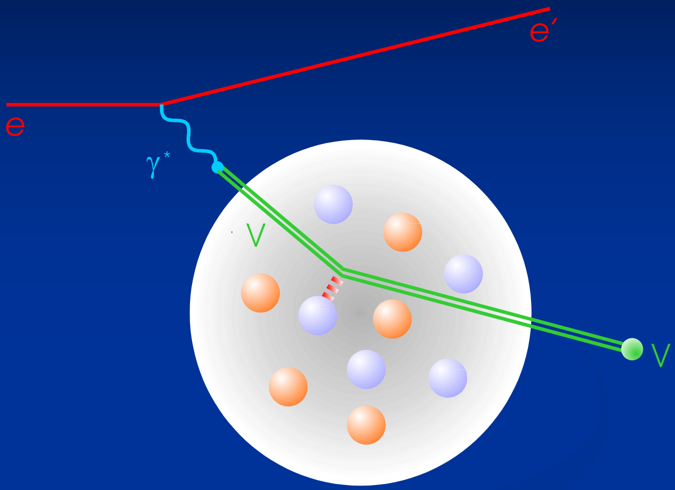


P. Muehlích, 2004

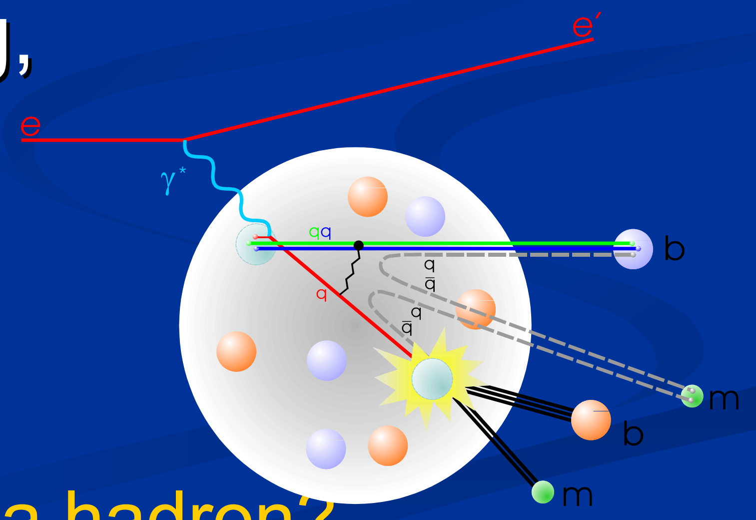
φ meson enhanced

High Energy γ Production Processes

- Diffractive VMD-Event
  - Main contribution to exclusive ρ^0-production

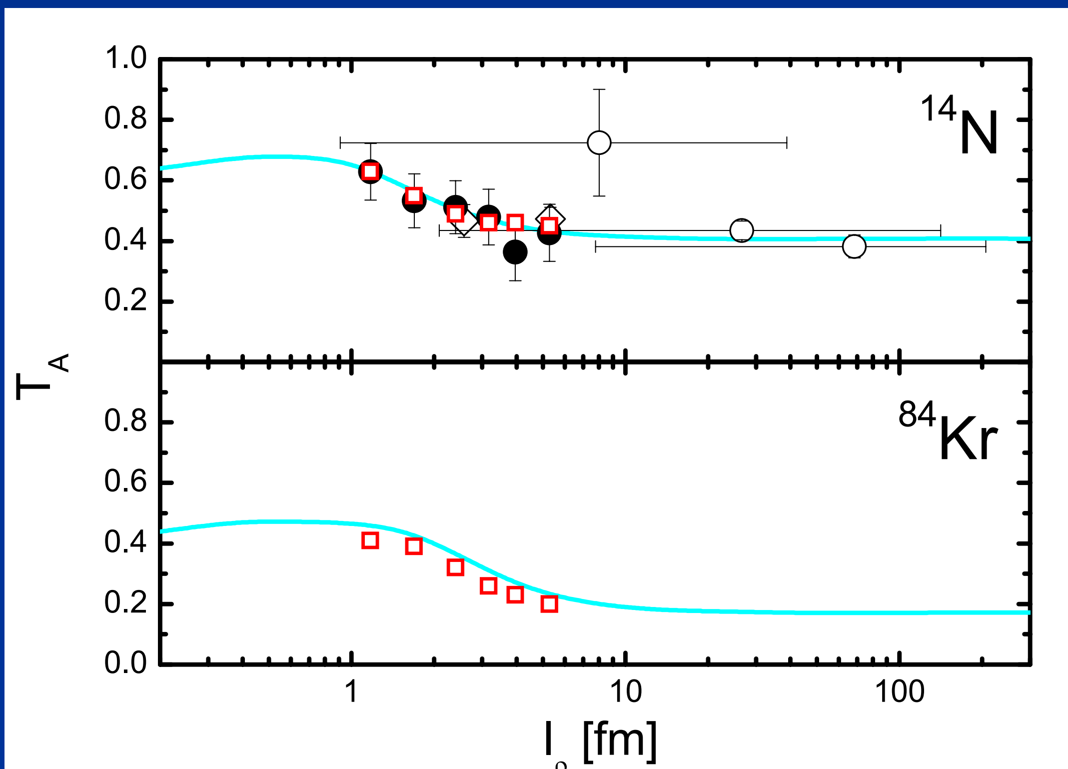


- Deep inleastic scattering, Jets



How long does it take to form a hadron?

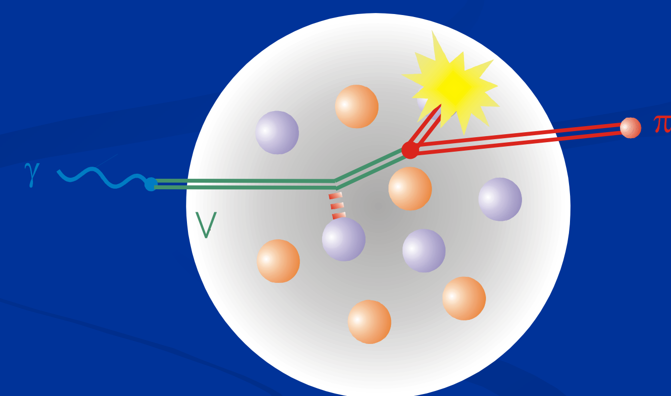
Color Transparency (?)



- Glauber:

$$\text{FSI} \sim \exp\left[-\sigma_{\rho N}^{\text{inel}} \int_z^\infty dz' n(\vec{b}, z')\right]$$

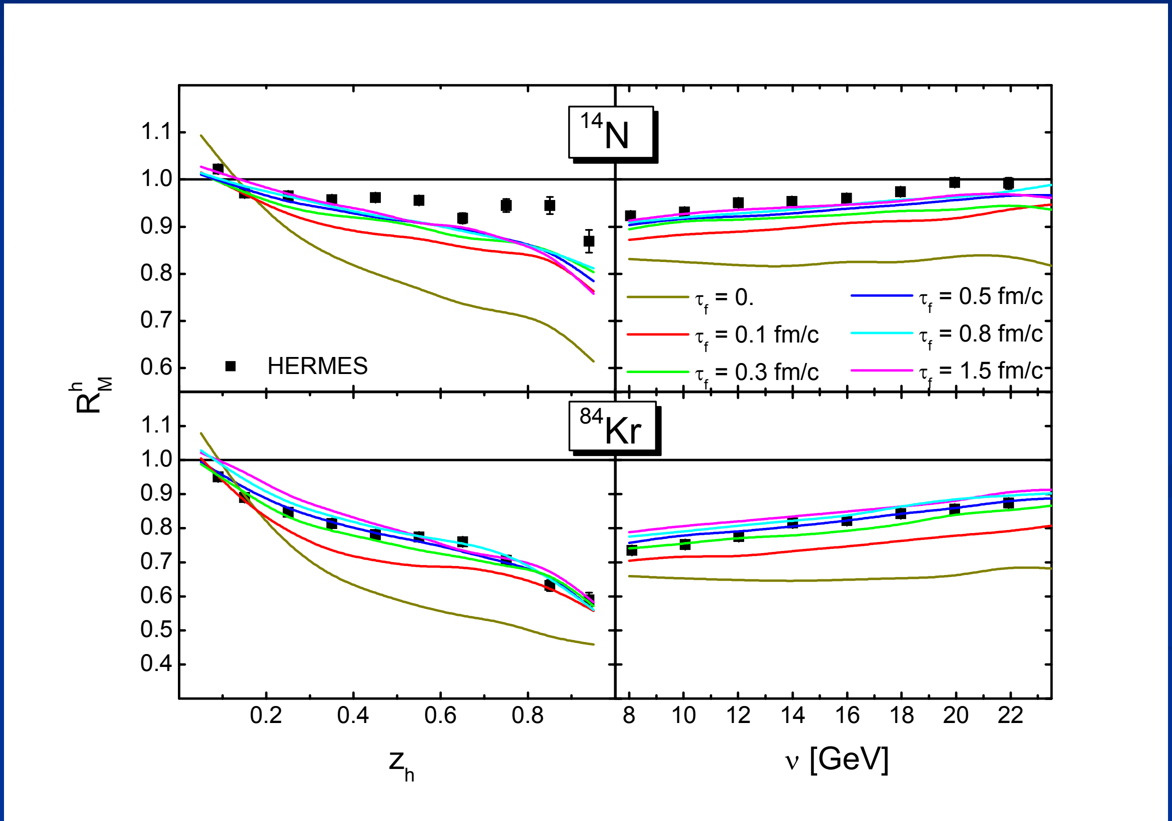
- BUU:



T. Falter et al, Phys.Rev.C67:054606,2003

In-medium fragmentation (HERMES)

Charged hadron ratios (to p)



Yields info on hadronization times
➔
nucleus as micro-detector

T. Falter et al,

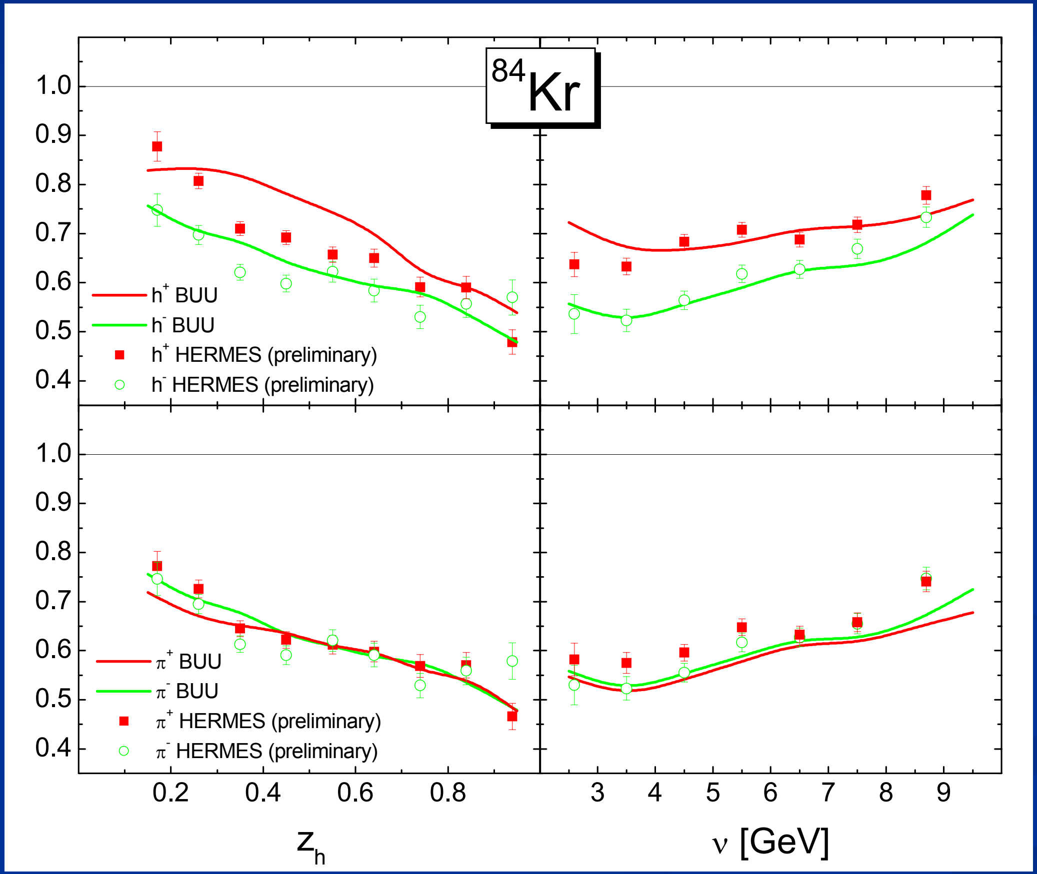
Phys.Lett.B594:61-68,2004

Formation time
$\tau_f > 0.3$ fm/c

Fast (pre)hadrons see nucleus

- HERMES @ 12 GeV (τ_f = 0.5 fm/c)

Model works also at lower energies

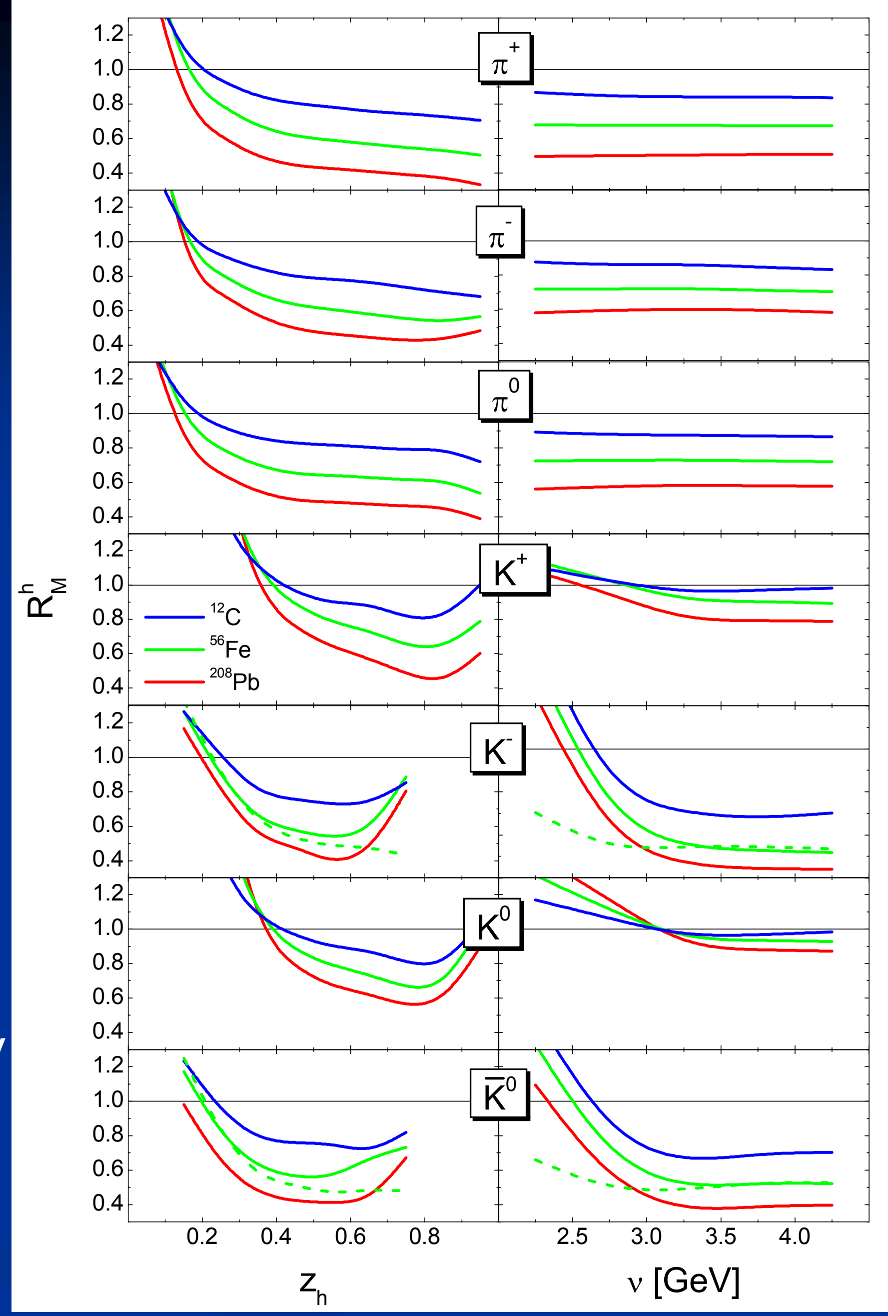


- Jefferson Lab (τ_f = 0.5 fm/c)
  - CLAS detector

    larger geometrical acceptance
    - detects more secondary particles from FSI
  - CEBAF

    lower energy E_e = 5 GeV ν_{max} = 4.25 GeV
  - strong effect of

    Fermi-motion



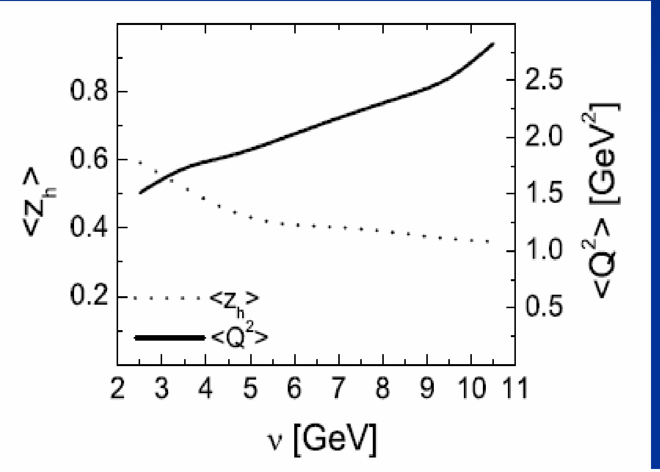
T. Falter, PhD thesis, Giessen, 2004

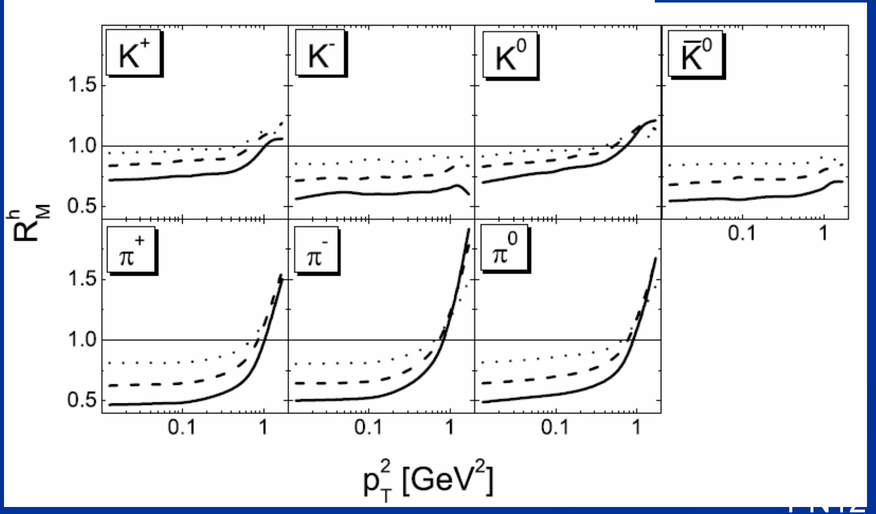
Jlab at 12 GeV

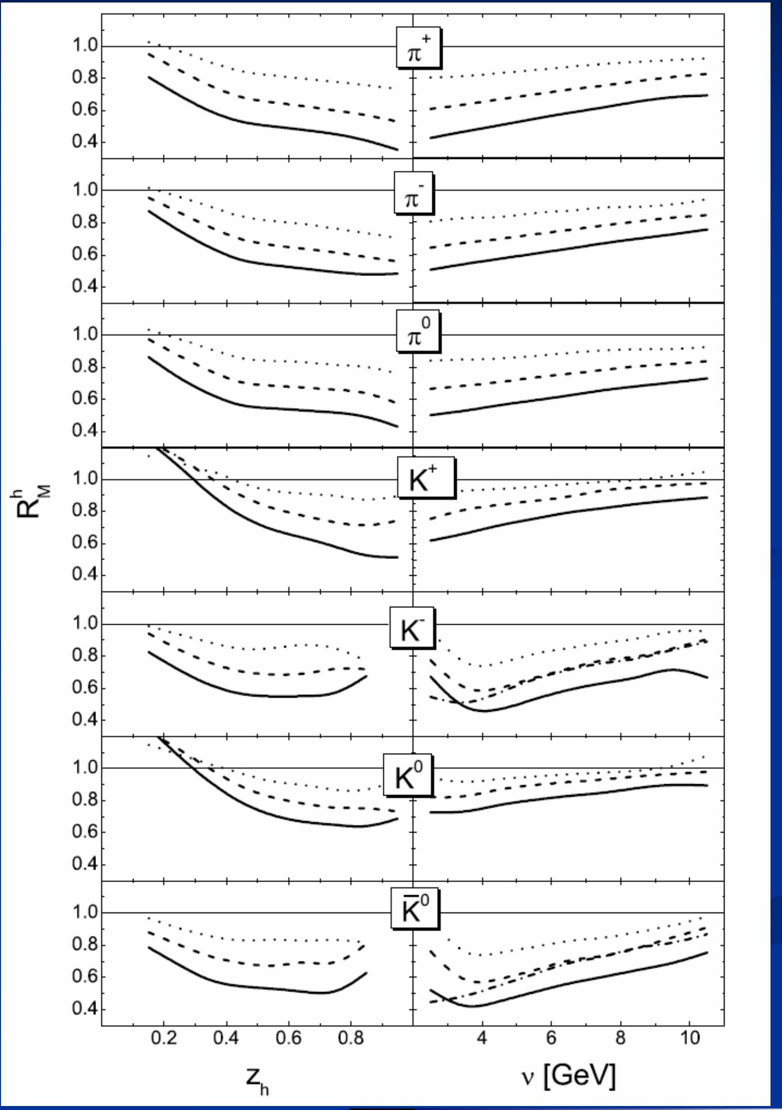
CLAS acceptance modelled

T. Falter, PhD thesis, Giessen, 2004

C
Fe
Pb







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Summary

- Method combines coherence in entrance channel (shadowing) with coupled channel (incoherent) transport in exit channel
- Reliable tool for interpretation of many-body processes: same physics (and code!) for photonuclear and heavy-ion reactions. Allows off-shell transport of broad resonances and implementation of experimental acceptance

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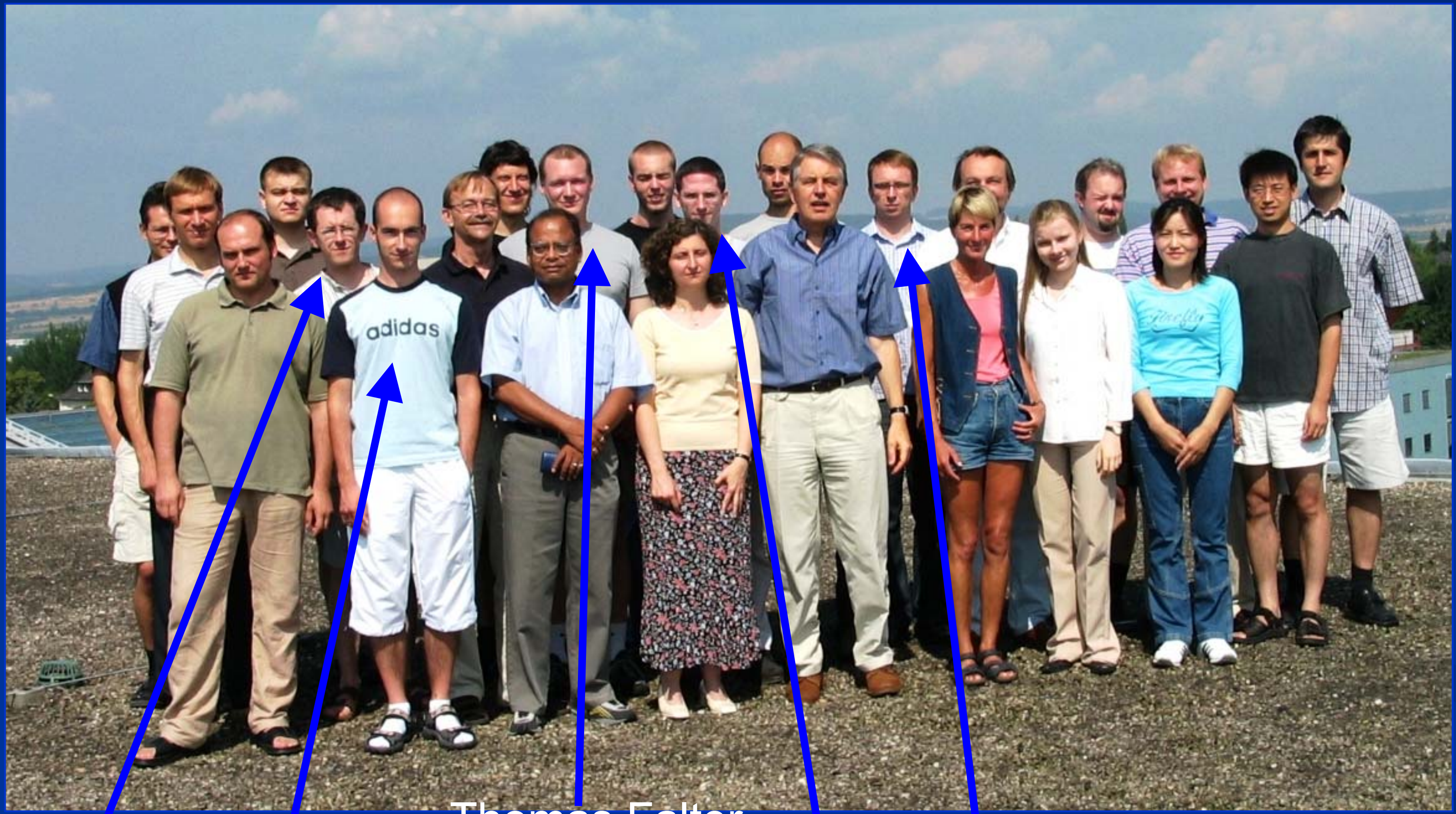
Summary

- Theoretical methods to calculate equilibrium in-medium properties quite advanced: selfconsistency possible, but still formidable many channel problem
- Chiral symmetry restoration in nuclei suggestive, but hard to pin down
- Reactions with microscopic probes (p, π, γ) provide baseline for ‚exotic‘ phenomena in URHICs
- At high energies access to formation times and CT



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